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RESEARCH MEMORANDUM

AN ANALYSIS OF THE TRACKING PERFORMANCES OF TWO STRAIGHT-WING AND TWO SWEPT-WING FIGHTER AIRPLANES WITH FIXED SIGHTS IN A STANDARDIZED TEST MANEUVER

By George A. Rathert, Jr., Burnett L. Gadeberg, and Howard L. Ziff

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SUMMARY

Standardized gunnery tracking runs against a target airplane have been conducted with F-51H, F8F-1, F-86A, and F-86E airplanes equipped with fixed gunsights. These tests were designed to document the tracking performance and, through statistical analysis, gain a better understanding of the sources of tracking errors. The runs were made over the normal operating range of altitude and Mach number of each airplane.

For steady-straight and steady-turning flight the average standard deviations of the aim errors were small (1 to 3 mils) for all airspeeds, altitudes, and test airplanes, and increased only slightly with normal acceleration (except for the F-86 pitch-up range). In the transition phase between straight and steady-turning flight, the tracking with the high-performance swept-wing airplanes was inferior to that with the straight-wing airplanes.

Power spectral densities of both aim wander and control-surface motions generally showed principal harmonic content at very low frequencies; secondary peaks which occurred around the airplanes' oscillatory frequencies were comparatively small except for the swept-wing airplanes in the transition region. Within the fairly wide ranges covered in these tests it appears that the airplane control-fixed dynamic characteristics have little effect on tracking performance.

[redacted]

INTRODUCTION

The problem of determining what stability and control characteristics are required of an airplane to insure that it will be an effective gun platform usually has been simplified to one of meeting the appropriate service's flying-qualities specification. These requirements need more critical examination for operations at high-speed and high-altitude where dynamic stability is decreased, more sensitive and powerful controls are used and considerably more complex fire-control systems are being matched to the airframe and pilot.

The influence of airplane characteristics on gun-platform suitability is being studied by the NACA in a series of flight investigations. These tests are to provide statistically significant data on the tracking performance of pilots using existing airplanes, identify the principal sources of aim wander, and isolate the effects of the significant characteristics of the airplane, either by comparison of data for different airplanes or by use of airplanes modified to vary the desired parameter in flight. In addition to providing design data, the tests are directed toward clarifying the relationship between quantitative tracking performances and the existing flying-qualities specifications which are principally derived from pilots' opinions.

This report presents the initial study, the tracking performance of typical fighter airplanes with fixed gunsights. The types of airplanes tested afford two comparisons of particular interest: that between typical World War II and currently operational fighters of greatly increased speed and altitude, and that between conventional and irreversible power-boosted controls with artificial feel, both installed on the same airframe.

Related tracking studies on different airplanes and different tracking problems are presented in references 1, 2, 3, and 4. The application of experimental techniques and the methods of data analysis used in this report have been materially assisted by the discussions in references 1, 5, and 6.

NOTATION

A_Z ratio of the net aerodynamic force along the airplane Z axis (positive when directed upward as in normal level flight) to the weight of the airplane

f frequency, cps

g acceleration due to gravity, 32.2 ft/sec^2

M free-stream Mach number

n number of observations

T_{A_Z} time interval during the gunnery run when the normal-acceleration factor is changing rapidly from 1g to the final steady-turn value

T_T total time interval in the transition from steady-level to steady-turning flight during which the aiming accuracy is disturbed

x tracking error in yaw, that is, the component, about the airplane normal axis, of the angular distance from the line of sight to the target, mils $\frac{1}{6400}$ of a Circle = 1 MIL

y tracking error in pitch, that is, the component, about the standard airplane lateral axis, of the angular distance from the line of sight to the target, mils

$\bar{x}$ bias error in yaw, that is, the algebraic mean, over the desired portion of the test run, of the tracking errors in yaw, $\frac{\Sigma x}{n}$, mils

$\bar{y}$ bias error in pitch, that is, as above, $\frac{\Sigma y}{n}$, mils

ϵ radial tracking error, $\sqrt{x^2 + y^2}$, mils

σ_x standard deviation or aim wander of the tracking error in yaw, that is, the root-mean square, over the desired portion of the test run, of the differences between the tracking and bias errors in yaw, $\sqrt{\frac{\Sigma(x - \bar{x})^2}{n}}$, mils

σ_y standard deviation or aim wander of the tracking error in pitch, as above, $\sqrt{\frac{\Sigma(y - \bar{y})^2}{n}}$, mils

σ^2 = Variance

TEST EQUIPMENT

Airplanes

The test airplanes, figure 1, were all single-engine, single-place, low-wing fighters. The two typical World War II fighters (the F8F-1 and F-51H) were propeller driven and had straight wings; the two more recent high-performance fighters (the F-86A and F-86E) were jet propelled and had 35° sweptback wings. Pertinent specifications are listed in table I;

additional photographs and drawings may be found in reference 7 for the F-51H and the F8F-1, and in reference 8 for the F-86A. The F-86E was not listed separately since the A and E models are alike insofar as the specifications appearing in the table are concerned; the only differences between the two lie in the control-surface actuation systems.

The F-86A has a conventional cable and linkage system, with the addition of a hydraulic boost for the ailerons and elevators to reduce the stick forces. The stabilizer and elevator are conventionally arranged, except that the entire stabilizer can be actuated electrically to provide longitudinal trim. The F-86E, on the other hand, has a completely irreversible hydraulic system to actuate the ailerons and horizontal tail and, therefore, also has an artificial feel system incorporated in order to provide normal stick-force feel to the pilot. Normal-acceleration stick forces are provided by a bobweight; control hinge-moment stick forces are simulated by automatically positioned bungees; and too-rapid motions of the stick are prevented by a stabilizer-rate damper. The elevators and movable stabilizer are linked together in such a fashion that they are jointly, but differentially, operated by the control stick (known as a controllable tail or flying tail). The kinematics of these two systems are compared in figure 2. The rudders on both airplanes are mechanically actuated in a conventional manner.

In order to provide targets of comparable performance and turning ability to the tracker, the F-51H and F8F-1 airplanes served as targets for each other and the F-86A and E airplanes were similarly paired off.

Gunsights

A fixed optical gunsight (U.S. Navy Mark 8 Mod 5) was installed in the cockpit of each of the airplanes, as shown in figure 3. This type of sight projects the image of a reticle on a small glass plate mounted on top of the sight. Figure 4 is the picture the pilot sees looking through the glass plate. The advantage of this type of sight is the elimination of pilot-position parallax - that is, the pipper appears to be fixed in relation to a distant object, regardless of the position of the pilot's head. The sights were installed with the sight line elevated 35 mils above the airplane thrust axes so that the tracking airplane would not be operating in the wake of the target.

Instrumentation

A 16-millimeter, electrically driven, motion-picture camera (GSAP) was mounted on each gunsight in the manner shown in figure 3. By use of a right-angle prism the body of the camera was placed outside of the

pilot's line of vision but the scene recorded was that which the pilot saw. The cameras were loaded with Kodachrome film and were set at f/11 and 16 frames per second. Color film was used because it was found to be easier to read than black-and-white film under the widely different exposure conditions encountered in flight.

Standard NACA recording instruments were provided to measure airspeed, altitude, normal acceleration of the center of gravity, and the position of each of the control surfaces. However, the Mach number and normal-acceleration factors used throughout this report are the nominal quantities noted by the pilots from indicating instruments installed in the cockpits. These were found to be accurate enough for the purposes of this report.

Pilots

In any evaluation of tracking performance where the pilot is part of the control loop, it is apparent that the pilot is not only the most important part of the test equipment but contributes very materially to the quality of the test results. It is, therefore, considered desirable to identify the pilots participating in the present tests (labelled as "A", "B", and "C" in the description of test conditions and the test results) and present brief summaries of their flight experience.

Pilot "A".- Rudolph D. Van Dyke, Jr. His flight experience, which began in 1940, was as follows: trained as a U. S. Navy carrier pilot, two years and 2000 hours flight time as instrument flight instructor, three years and 1200 hours flight time as carrier fighter pilot with 170 hours actual combat time, seven months and 300 hours airline copilot experience, five years and 2000 hours as research pilot, of these 270 hours in jet aircraft, total flight time 5800 hours.

At the conclusion of the present tests this pilot was sent to the 3525th Aircraft Gunnery Squadron at Nellis Air Force Base, Las Vegas, Nevada, for indoctrination and a calibration of his performance in actual air-to-air gunnery firing tests in comparison with average U. S. Air Force pilots. He was rated above average when compared with experienced U. S. Air Force fighter pilots.

Pilot "B".- George E. Cooper. His flight experience, which began in 1943, was as follows: trained as U. S. Army Air Corps fighter pilot, five months, 300 hours, as instructor in fighter-type aircraft, one year in combat theater as fighter pilot with 250 hours actual combat time, seven years and 2000 hours as research pilot with 400 hours in jet aircraft, total flight time 2800 hours.

Pilot "C".- Donovan R. Heinle. His flight experience, which began in 1942, was as follows: trained as U. S. Navy Aviation Cadet, 50 hours in combat theater - none of which was air-to-air gunnery, 620 hours over a period of three years, one year and 225 hours as instructor for primary students for CAA private license, twenty months and 170 hours time reserve flying - fighter training, six months and 135 hours as research pilot, total flight time 1200 hours.

TESTS

It was decided that, for each test run, a standard repeatable maneuver should be performed so that (1) as many flight conditions as possible, such as Mach number, altitude, and normal acceleration, could be kept reasonably constant for purposes of comparison, and (2) statistically significant amounts of data could be obtained in reasonable amounts of flight time at the selected flight conditions.

The standardized test maneuver chosen is sketched in figure 5. The target airplane began the run by flying straight and level at the desired altitude and Mach number, with the tracking airplane approximately 1,000 feet behind, and offset 100 mils to either left or right. After a few seconds, the tracker swung toward the target and began to track in straight 1g flight. After flying straight and level for roughly 35 to 40 seconds, the target airplane (with no prior warning and as rapidly as possible) began a constant-g turn to either right or left and held this turn for approximately 35 to 40 seconds. The standard gunnery run, therefore, consisted of a transition portion ending in straight and level flight; a straight and level portion; then a transition to steady-turning flight; and finally a steady-turn portion.

Altitude was maintained during the 1g portion of the run, except at the highest Mach numbers. During the turns, only enough altitude to maintain constant Mach number was lost. (No more than 4000 feet of altitude was lost in any one record interval.) The range was kept as close to 1000 feet as possible throughout the maneuver. The aiming point on the target was the tailpipe exit in the case of the jet-propelled aircraft and the intersection of the stabilizer and vertical fin in the case of the propeller-driven aircraft.

The test program consisted of the conditions of Mach number, normal acceleration, and altitude listed in table II. As noted in the table, most of the program was completed by each of two pilots, and the F8F-1 and F-51H portions were repeated by a third pilot. The tests were confined to the normal operating ranges of normal-acceleration factor below the buffet boundaries, except for a few specified test points on the swept-wing airplanes. The ranges of pertinent flying qualities covered by the test conditions, longitudinal stick-force and gearing gradients

and lateral-directional period and damping, are shown in figures 6 and 7, respectively. The appropriate service specifications from reference 9 are included.

All of the test data were obtained in smooth-air conditions that were considered by the pilots to be typical of the majority of flight time at the test altitudes.

DATA REDUCTION METHODS

The gunsight-camera film was assessed on a projection-type film reader. A movable reticle calibrated in mils was placed directly over the image of the gunsight reticle with the origin coincident with the image of the gunsight pipper, and the distance from each of the movable reticle axes to the aiming point on the target was read off directly in mils. This procedure was repeated for every third frame of the camera record. The film speed was 16 frames per second. The aim errors were then plotted against time, as typified in figure 8. This figure shows both the aim errors and the time history of normal acceleration of the tracking airplane.

By visual inspection and comparison to the A_Z time variations, each of the aim-error time histories was divided into four sections, as shown in figure 8. The example is typical in that determining the interval T_T often required personal judgment. The aim errors for each section were then defined by the algebraic mean, hereafter called the bias error,

$$\overline{x} = \frac{\Sigma x}{n} \text{ and } \overline{y} = \frac{\Sigma y}{n}$$

and the standard deviation from the mean, hereafter called the aim wander,

$$\sigma_x = \left[\frac{\Sigma(x-\overline{x})^2}{n}\right]^{\frac{1}{2}} \quad \text{and} \quad \sigma_y = \left[\frac{\Sigma(y-\overline{y})^2}{n}\right]^{\frac{1}{2}}$$

The errors were expressed in rectangular coordinates (pitch and yaw) instead of polar coordinates in order to associate them with a particular airplane control function and in angular measure (mils) in order to minimize the effects of range.

The mean and the standard deviation have been used since aim errors would be expected to follow a random process and show a Gaussian distribution. Probability plots of the aim errors typified by figure 9 indicate a reasonable agreement with the Gaussian distribution; thus,

it can be assumed that the aim error will be within plus or minus one standard deviation of the mean value for 68.4 percent of the time.

The predominant frequencies present in the aim wanders and the control-surface motions were determined by computing the power spectral density, a function representing the power or relative contribution of a single frequency to the whole. The significance of this quantity and its usefulness in gunnery analysis are discussed in references 1 and 5. Because the data obtained in the present investigation had a relatively short time base and were read at discrete intervals of time, the statistical methods of calculating the autocorrelation functions and power spectral densities presented in reference 6 were used. Computations were carried out with the aid of an IBM electronic computer.[1] In view of the detailed treatment in reference 6 further discussion here is omitted.

For the steady-straight and steady-turn portions of the test runs, sufficiently long continuous records were obtained to make the analysis valid for both of the frequencies predominant in the aim-wander data. For the transition portions, which in most cases lasted for only 5 to 15 seconds, statistically significant lengths of records could be obtained only by adding graphically in series the data from several transitions.

Consider

Three phases of the aim-wander measurements have been investigated for accuracy. Since the pippers were 1-1/2 to 2 mils wide and the aiming points (tailpipe exits) as much as 2 mils in diameter, there was a definite limit on the size of aiming error which was apparent to the pilot and resulted in corrective action. Repetitive experiments at different ranges indicate that the pilots allowed the center of the pipper to drift a maximum of 1-mil radius from the center of the aiming point without considering a tracking error to exist. The aim errors on individual frames of the gun-camera records were read with a similar accuracy, ±1 mil. In order to check the accuracy of the aim-wander calculations, one 45-second length of film was completely analyzed twice. The difference between the two resulting aim wanders was only 0.3 mil.

RESULTS AND DISCUSSION

Mean

The analysis consisted of the determination of the bias errors and the aim wanders and the identification of the sources of the aim wander by means of power spectral densities. This has been done for three conditions of normal acceleration: (1) steady-level flight and (2)

[1]The adaptations of these methods to IBM computing machinery were developed by Dr. W. A. Mersman of Ames Aeronautical Laboratory, Electronic Computing Machine Section.

constant-acceleration turns, which were analyzed together, and (3) transition regions wherein the normal acceleration was undergoing rapid unidirectional changes.

Level Flight and Constant-Acceleration Turns

MEAN
Bias errors.- The ~~bias~~ mean errors in level flight and constant-acceleration turns are not presented in this report since no significant trends were discovered. The data are summarized by airplane in the following table:

Airplane	$\bar{x}_{average}$	$\bar{y}_{average}$
F-51H	-0.2(-1.2 to 0.6)[a]	0.5(-0.5 to 1.8)
F8F-1	0.4(-0.4 to 1.4)	1.6(0.1 to 3.9)
F-86A	0.6(-1.3 to 2.2)	2.6(0.6 to 4.7)
F-86E	-0.4(-2.1 to 0.7)	0.8(-1.1 to 2.9)

[a]Wherever averaged data are compared, the amount of scatter present has been indicated by placing in parenthesis the range of values which include 90 percent of the observed data, thus, $\bar{x}_{average}$ = -0.2 with 90 percent of the test points falling between -1.2 and 0.6.

The averaged errors vary from -0.4 to 2.6 mils with the median value near 1/2 mil. Since the gunsight pipper and the aiming point are 2 mils wide, the errors are probably within the limit of the pilots' ability to perceive when an error is large enough to require correction. For this reason the ~~bias~~ mean error data are considered not to reveal anything significant about the flying qualities of the test airplanes.

Aim wander.- Plots showing the variation of the aim wander with normal-acceleration factor at noted Mach numbers and altitudes are presented in figures 10 through 13 for each airplane and pilot. When the possible effects of flight conditions or pilots are considered, the measured aim wanders are seen to be small, 4 mils or less, under all conditions tested, except for the two F-86 airplanes (figs. 12 and 13) at normal accelerations above the normal operating range, that is, above the buffet boundary where the airplanes were in a partially stalled condition. Within the normal operating ranges, however, even the variations of aim wander with normal acceleration are small and are less than that indicated by the empirical formula suggested in reference 10. There were no significant differences in the tracking abilities of the three test pilots, despite the fairly wide range of actual flying experience.

Since the effects of flight conditions and pilots can be neglected, the following table summarizes the complete averages by airplane:

Airplane	$\sigma_{x_{average}}$	$\sigma_{y_{average}}$
F-51H	1.6 (0.7 to 2.7)	1.3(0.5 to 2.4)
F8F-1	1.9 (1.0 to 3.0)	1.6(0.9 to 2.7)
F-86A	2.6 (1.1 to 5.2)	2.7(1.0 to 4.2)
F-86E	2.6 (1.0 to 4.3)	2.5(0.9 to 4.5)

The aim wanders for the two World War II fighters are somewhat less than those for the high-performance fighters; however, the values for all four airplanes are of the order of magnitude reported in references 2 and 3 for the F9F-2 and F2H-2 airplanes. It is also apparent that the results for the F-86A and E are quite similar, indicating that the difference in control systems between the conventional power-boosted elevators with stick-force feedback and the irreversible flying tail with artificial stick-force feel did not affect the pilots' ability to track. The comparison is of tracking performances; differences in pilot effort or pilot opinion were not evaluated.

The foregoing data indicate that the tracking performance under steady-state conditions is satisfactory within the range of flying qualities represented by the four test airplanes at their normal operating conditions of airspeed and acceleration. The ranges of pertinent flying qualities covered were presented in figures 6 and 7. For a comparison with the aim wanders shown, the standard deviation of typical ballistic dispersions for a single 50-caliber machine gun is given in reference 11 as 2 to 3 mils.

No additional data at flight conditions beyond the normal operating ranges could be obtained on the F-51H and F8F-1 airplanes since, as inferred from reference 12, the build-up of buffet intensity above the buffet boundary is so rapid that there is no appreciable operating margin between the buffet boundary and the flight-test limits. The F-86 airplanes, on the other hand, could be operated above the buffet boundary where they were subject to buffeting, lateral unsteadiness (either a mild roll-off or a tendency to overcontrol laterally), and a longitudinal instability or pitch-up problem which is discussed in reference 8. Certain of the test points in figures 12 and 13 are marked to indicate where these or other problems were encountered according to the pilots' notes.

It is obvious that the flying qualities in this partially stalled regime critically limit the gun-platform effectiveness. The test points in figures 12 and 13 which exceed 4 mils reveal that encounters with the

slipstream, stalls, and varying degrees of pitch-up contributed the most to the aim wander. In general, the occurrence of buffeting and lateral unsteadiness either alone or together did not cause the aim wander to exceed 4 mils although, in the case of the lateral unsteadiness, records of the aileron movements support the pilots' opinion that they had to work significantly harder.

Attempts to obtain more data at higher normal accelerations in fully developed pitch-ups were unsuccessful and at times resulted in aim errors larger than the field of view of the camera (100 mils), indicating that the pitch-up introduces such gross errors that tracking is impossible. Further, in this case the provision of an irreversible control with artificial stick-force feel was not a satisfactory solution to the problem from a gunnery standpoint since tracking was impossible with either the conventional tail or the flying tail, despite the pilot preference for the latter in the pitch-up regime.

Power spectral densities.- The principal frequencies present in the steady-state aim-wander time histories can be determined from the typical power spectral densities presented in figures 14(a) through 17(a). Each of the aim-wander spectral-density curves has two predominant peaks, the lower frequency generally being of higher power or greater significance.

The sources of these two significant frequencies are readily identified. By comparison of the aim-wander curves with the corresponding control-motion curves presented in the (b) part of each figure it is seen that the lower frequency, 0.1 to 0.2 cycle per second, is of the same order of magnitude as the rate at which the pilot operated the control surfaces. The higher frequency, 0.7 to 1 cycle per second, corresponds fairly well to the short-period-oscillation frequencies of the airplanes, if allowance is made for the sensitivity of the airplane periods to control-surface motions and shifts in the center-of-gravity positions which were present in the gunnery tests.

In general, the relative power of the short-period frequencies is much less than that of the lower frequencies (of the order of 1:10), and it is concluded that the airplane dynamic characteristics have little effect on the aim wander under the test conditions. This appears to be true whether the short-period oscillations are well or lightly damped. Figure 7 shows that the dynamic characteristics investigated include those that would be rated unsatisfactory by current U. S. Air Force requirements (ref. 9) and were regarded as unsatisfactory for formation or instrument flying by the pilots in the present tests. Since the tracking was satisfactory under these conditions, it appears that dynamic-stability flying-qualities specifications required to obtain gun-platform effectiveness would be less severe than those already imposed for other types of flying. The range of lateral-directional oscillatory characteristics covered here has been greatly extended by similar tracking tests with an airplane equipped so that the pilot could vary period,

damping, and roll-to-yaw ratio and could introduce standardized rough air. The results are discussed in reference 13.

Some exceptions where the short-period frequencies become prominent can be noted for the F-86 airplanes, particularly the F-86E in figure 17(a). The two conditions of interest are at 0.97 and 0.70 Mach number at 35,000 feet. At 0.97 Mach number the wing-dropping phenomenon described in reference 14 occurred. The power spectral densities in figures 17(a) and (b) clearly show an increase in the relative amount of aileron-control motion and a correspondingly greater excitation of the short-period frequencies in the yaw aim wander. The similar tendency at 0.70 Mach number is ascribed in the pilots' notes to a strong lateral overcontrolling tendency, a control sensitivity problem at that condition. It is emphasized, however, that the aim wanders for both of these conditions remained below 4 mils, as shown in figure 13.

Of additional interest is the much greater relative use of the rudder control on the World War II fighters, figures 14(b) and 15(b), compared with the available data for the F-86A airplane, figure 16(b). Again, there is a correlation with pilot opinion in that apparently very little use of the rudder is attempted where the effectiveness is reduced and the directional damping is low.

Since the predominant frequency present in the aim wander corresponds to that of the pilot-applied control-surface movements, several questions for further research arise. Of particular interest would be investigations of the effects of piloting technique or gunnery-training methods and such characteristics of the control system as sensitivity, stick gearing, force gradients, centering, and friction. However, the summary plot of longitudinal-control characteristics, figure 6, indicates that some of the flying qualities which yielded satisfactory tracking during these tests are rated unsatisfactory for other types of flying. A further question would be the validity of the present conclusions when methods of target presentation other than direct visual sighting are used.

Transition Region

If it is assumed that the attacking airplane has a fire-control system which can respond to the tracking signals quickly enough, air-to-air combat may require satisfactory tracking under conditions of rapidly changing normal acceleration as well as the steady-state conditions discussed in the preceding section. Although the problem of evaluating all probable evasive maneuvers with significant and repeatable flight tests is obviously formidable, some significant data on the tracking performance under such conditions can be obtained by examining the transition region of the gunnery run used in the present tests.

The transition region is defined as the period during which the tracking performance is disturbed due to the change from steady wings-level flight to steady-turning flight. Figure 8 illustrates typical transition-region aim errors in relation to the time history of the normal acceleration of the tracking airplane.

Mean σ_x or σ_y – Standard Deviation

The basic data available for evaluating the tracking performance are the time within the region, bias error, and aim wander. Additional criteria are presented, however, since long transition times may be tolerated if accompanied by small aim errors, and very large errors may be tolerated if present but for a short time. Since the steady-state results indicated that the pilot differences were not significant, data are presented for pilot "A" only.

Transition time.- The total time in the transition region is defined as

$$T_T = T_1 + T_{A_Z} + T_s$$

where T_1 is the time during which sighting disturbances are introduced, due to the initial rolling of the tracker before the normal acceleration begins to change; T_{A_Z} is the "maneuvering time" during which the normal acceleration is changing; and T_s is the time after the normal acceleration has reached its final value, during which residual oscillations are present in the aim wander.

Two transition-time parameters are presented in figure 18: the total transition time, T_T, and the ratio of total to maneuvering times, T_T/T_{A_Z}. The ratio of T_T/T_{A_Z} is a comparison of the extent to which the airplane characteristics lengthen the time in which tracking is disturbed beyond the time actually required to maneuver. A value of $T_T/T_{A_Z} = 1.0$ represents no increase in time during which the sighting is disturbed due to the airplane characteristics. The averaged values of T_T and T_T/T_{A_Z} are summarized by airplane in this table:

Airplane	$T_{T_{average}}$	$(T_T/T_{A_Z})_{average}$
F-51H	10.5(4.0 to 18.5)	2.2(1.1 to 5.0)
F8F-1	10.8(7.3 to 14.0)	2.2(1.2 to 3.6)
F-86A	14.3(8.3 to 24.0)	3.5(1.5 to 6.4)
F-86E	11.1(5.7 to 19.0)	2.7(1.5 to 4.2)

Although there is some variation between airplanes, it is apparent that the scatter is too large to justify comparing tracking performances on a time basis alone. The scatter is attributed both to actual differences in the experimental results and the difficulty in consistently judging the time T_T from the recorded data.

Mean

Bias errors.- The bias errors within the total transition time T_T are presented in figure 19 and summarized by airplane as follows:

Airplane	$\bar{x}_{average}$	$\bar{y}_{average}$
F-51H	-0.2(-1.5 to 1.2)	1.4(-0.2 to 3.0)
F8F-1	-0.3(-2.0 to 2.2)	2.2(1.0 to 4.1)
F-86A	0.0(-2.4 to 3.1)	2.4(-0.5 to 6.4)
F-86E	0.0(-3.3 to 1.6)	1.0(-1.9 to 3.5)

The average values varied from -0.3 to 2.4 mils with the median value near 1/2 mil. Except for the larger amount of scatter, these data are considered comparable to the steady-state values and subject to the discussion presented in that section. This result may be considered surprising and the probable reasons for it deserve scrutiny.

For a fixed, noncomputing sight the primary source of bias error in the transition to turning flight would be expected to be lag in tracking. Several factors tend to minimize such lag in the present tests. The human pilot is able to detect the initial rolling movement of the target prior to the time the target develops normal acceleration and moves away from the pipper. With this warning before an actual error appears he can be ready to keep the error small by skidding the tracking airplane or turning it more rapidly at first until his own acceleration builds up. Also, in these particular tests the tracking and target airplanes had quite similar performance and maneuverability characteristics. The further fact that the sight line was elevated 35 mils above the thrust line to minimize the effects of the target wake also may have contributed to reducing the lag since with an elevated sight line a small yaw correction can be made very quickly by rolling. The net effect of this elevation on the over-all tracking performance in not known, however, and may merit further study.

Another important factor in the small bias errors observed is believed to be the pilot technique, particularly the choice between abrupt and rapid error corrections or slow and smooth control motions to avoid exciting airplane oscillations. The latter technique has been recommended in pilots' handbooks for the operation of disturbed-reticle computing gunsights.

In the present tests which involve fixed sights only, the pilots chose to reduce the significant errors or pipper displacements as abruptly as possible without being concerned about the airplane oscillations. In the opinion of the NACA pilots this choice of test technique merits emphasis when evaluating relative tracking performances using a fixed-reticle sight, particularly in tracking with airplanes having lightly damped oscillatory motions and sensitive control systems.

Aim wander.- The aim wanders for the transition period T_T are shown in figure 20 as functions of the final normal acceleration. The values averaged by airplane and their ratios to the steady-state values tabulated on page 10 are:

Airplane	Transition region		Transition / steady state	
	$\sigma_{x_{average}}$	$\sigma_{y_{average}}$	$\sigma_{x_{average}}$	$\sigma_{y_{average}}$
F-51H	2.2(1.2 to 3.0)	2.0(1.2 to 3.4)	1.4	1.5
F8F-1	2.6(1.2 to 4.0)	2.3(1.3 to 3.6)	1.4	1.4
F-86A	5.4(1.9 to 8.7)	6.1(2.6 to 7.4)	2.1	2.2
F-86E	4.5(1.7 to 7.3)	4.3(1.7 to 7.9)	1.7	1.7

The average transition aim wanders are significantly larger than the steady-state values by a factor of 1.4 for the World War II fighters and 1.7 to 2.2 for the F-86A and F-86E. The probable source of the increase in aim wander will be scrutinized by means of the power spectral densities of the errors.

Power spectral densities.- Figures 21 through 24 are typical power spectral densities for the aim wander and control-surface motions during transition periods. As explained in the section on data reduction methods, it was necessary to add, in series, data for several transition periods in order to provide a significantly long time interval.

By comparison of these data with figures 14 through 17 it can be seen that in the case of the F-86 airplanes, the frequencies of the order of the short-period oscillations of the airplane contribute a significantly larger portion of the total aim wander for the transition region than for steady-state conditions. Since the portion contributed by the frequencies of the control-surface motions remains unchanged, it is concluded that the relative increase in total aim wander is probably caused by increased excitation of the short-period oscillations of the airframe.

Discussions with the pilots have indicated that, as compared to the steady-state conditions, the turn entry requires additional concentration by the pilot on gross errors and more manipulation of the

control surfaces. It is believed that this increased amount of control movement is responsible for the greater excitation of the short-period oscillations.

Tracking-performance criteria.- The task of discriminating between transition tracking performances has been greatly simplified for the present tests by the fact that the differences in the transition times were small and in the bias errors negligible; therefore, the aim-wander data discussed previously were used to convey and explain nearly all the differences in tracking. Since this will not always be true, particularly for tests of computing sights or automatic guidance systems, it is desired to combine the preceding data and re-present them in forms which will be more useful for making general comparisons.

The most general basis for discrimination under transient conditions would be total time and total radial error. One expression of this type, the "integrated-square error" $\int_0^T \epsilon^2 dt$, has been suggested in reference 15 for analyzing transient responses in automatic guidance systems. This expression is presented as a function of final normal-acceleration factor in figure 25. The following table summarizes the values for all the runs averaged by airplane:

Airplane	$\int_0^{T_T} \epsilon^2 dt$
F-51H	124 (34 to 257)
F8F-1	181 (56 to 427)
F-86A	1002 (135 to 2722)
F-86E	496 (91 to 1303)

To permit comparisons of total errors between transition and steady-state conditions, it is necessary to use the mean value of the above expression, $\overline{\epsilon^2} = \frac{1}{T_T}\int_0^{T_T} \epsilon^2 dt$, or the more familiar rms error, $\sqrt{\overline{\epsilon^2}}$, presented in figure 26. The following table presents a comparison of the rms errors under both transition and steady-state conditions averaged by airplane for all of the test runs:

Airplane	rms error = $\sqrt{\frac{1}{T_T}\int_0^{T_T} \epsilon^2 dt}$		
	Steady state[a]	Transition	$\frac{\text{Transition}}{\text{steady state}}$
F-51H	2.5 (0.8 to 4.0)	3.1 (2.1 to 4.4)	1.2
F8F-1	2.9 (1.3 to 4.8)	3.8 (2.6 to 5.5)	1.3
F-86A	4.5 (2.4 to 7.1)	7.4 (4.6 to 15.5)	1.6
F-86E	3.7 (1.3 to 6.7)	6.2 (3.5 to 12.3)	1.7

[a]Since no basis for limiting the time was available for steady-state conditions, the rms errors were arbitrarily determined for T_T = 10-second time intervals over a representative range of test conditions.

The ratios between the steady-state and transition values agree reasonably with the comparison of aim wanders tabulated on page 15, as would be expected in the absence of significant bias errors.

The integrated-square-error expression has some disadvantages for the problem of most interest in this section, the discrimination between airplanes in the transition region. It weighs as undesirable the error squared over the total time T_T. This means that in a given comparison, the tracker may be penalized for differences in maneuvering time T_{A_Z} which result from increased flight-test speeds, nonstandard target behavior, and errors in range, factors which are difficult to control in an experiment and are not attributable to the tracker as liabilities for the present purposes. For this reason a "figure of merit"

$$F.M. = \frac{100}{\sqrt{\overline{\epsilon^2} \times \frac{T_T}{T_{A_Z}}}}$$

has been devised specifically to compare configurations with different stability and control characteristics. It combines the two desirable characteristics of low aim error and minimum time in which sighting is disturbed; however, the effects of the length of the maneuvering time are removed by the use of averaged errors and the time-ratio parameter.

The values of this expression are presented in figure 27. A large value of the figure of merit is favorable. The summary by airplane follows:

Airplane	F.M.
F-51H	19.0 (8.2 to 38.5)
F8F-1	16.0 (5.7 to 27.5)
F-86A	6.6 (1.5 to 15.9)
F-86E	8.1 (3.1 to 17.1)

There is a significant distinction by a factor of 2 to 3 between the tracking performance of the World War II fighters and the more recent high-performance fighters which correlates well with the pilots' opinion for this condition. The relatively poor tracking of the high-performance fighters under transition conditions apparently results from the larger aim wanders which in the discussion of the power spectral densities were attributed to increased excitation of the short-period oscillations of the airframe caused by control movements.

Reliability of Data

Several factors are present in any collection of statistical data relating to tracking performance which raise questions as to the validity of any conclusions that may be drawn. Among these factors are the effect of different ranges, the repeatability of the data, and the effect of pilot learning during the time that the test results were collected. It will be shown that the variations due to these factors are all small and within the normal scatter of the data (excluding those cases where serious flow disturbances were reflected into the test data).

Effect of range.- Several runs were made at various ranges, 35,000 feet altitude, 0.87 Mach number, and 2g normal acceleration. The resultant aim wanders are shown in figure 28 as a function of the range. The flat central portion of the curves (from 800 to 1600 ft) includes the scatter in the ranges used to collect the data previously discussed. It is thus apparent that the variation of range had but a very small effect on the data. It should be emphasized that the pilots attempted to track a point target on the target airplane regardless of range. One factor in the increase in the aim wander at very short range was due, according to the pilots' report, to immersion in the wake of the target airplane.

Repeatability of the data.- Since each different steady accelerated turn was preceded by a 1g level flight run, a considerable number of the latter data are available for use in assessing the repeatability of the data. These results are summarized in figure 29. The scatter in the aim wanders at a given condition is of the same order of magnitude as the over-all variations with changing flight conditions for steady-state flight.

Pilot learning.- An attempt was made to determine the effect of the pilot learning to accomplish his task during the course of the tests. This was done by repeating, late in the test program, runs that had been taken early in the program. The results of these runs are listed in table III. The variations are within the normal scatter of the data, and it was concluded that the pilots' ability did not change significantly during the course of the test program.

CONCLUSIONS

A study of the air-to-air tracking performances of two typical World War II and two swept-wing fighter airplanes in smooth air using fixed sights and visual target presentation has indicated that:

1. The bias (mean) errors were not significant either under steady or rapidly maneuvering conditions. The average values varied from -0.4 to 2.6 mils; the median value was 1/2 mil.

2. Within the normal flight operating conditions of airspeed and acceleration in steady level flight and constant-acceleration turns, there were no significant variations of aim wander (standard deviation from the mean) with normal acceleration, Mach number, altitude, or pilots. The averaged aim wanders by airplane were comparable to the ballistic dispersion of a single 50-caliber machine gun (2 to 3 mils):

Airplane	σ_{yaw}	σ_{pitch}
F-51H	1.6	1.3
F8F-1	1.9	1.6
F-86A	2.6	2.7
F-86E	2.6	2.5

Power spectral densities of both the aim wanders and the control-surface motions generally showed principal content at low frequencies (0.1 to 0.2 cps); secondary peaks occurred at about the airplane oscillatory frequencies but were comparatively small.

3. The pitch-up or longitudinal instability encountered above the buffet boundary by the swept-wing airplanes definitely limited the gun-platform effectiveness. The tracking errors in this region were unacceptably large with either a conventional force-feedback, hydraulically boosted elevator control system, or an irreversible and aerodynamically much more powerful controllable tail (flying tail) with artificial control-force feel.

4. Under transition conditions of rapidly changing normal acceleration, there were significant increases in the aim wander, by a factor of 1.4 for the World War II fighters, and 1.7 to 2.2 for the later high-performance fighters. The deterioration in tracking for the high-performance fighters was attributable to sizable excitation of the lightly damped short-period oscillations of the airframe caused by the control movements necessary in this relatively rapid maneuver.

5. Within the ranges covered by these tests, which included lateral-directional oscillatory characteristics that did not meet current flying-qualities specifications, the airplane dynamic characteristics had little effect on the tracking performance.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Aug. 12, 1953

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TABLE I.- PERTINENT SPECIFICATIONS OF TEST AIRPLANES

Specification	F-86A and E	F8F-1	F-51H
Gross weight, lbs	14,000	9,100	8,660
Airfoil section (root) (Normal to 1/4-chord line)	NACA 0012-64 (Modified)	NACA 23018 (Modified)	NACA 66.2-(1.8) (15.5) (a = 0.6)
Airfoil section (tip)	NACA 0011-64 (Modified)	NACA 23009 (Modified)	NACA 66.1-(1.8) (12.0) (a = 0.6)
Total wing area, sq ft	287.9	244.0	235.0
Span, ft	37.1	35.5	37.0
Aspect ratio	4.79	5.17	5.82
Sweepback of 1/4-chord line, deg	35.2	0	0
Sweepback of leading edge, deg	37.7	5.1	3.7
Dihedral, deg	3.0	5.5	5.0
Twist, deg	2.0	0	-2.5
Incidence, deg	1.0	3.0	1.0
Taper ratio	0.51	0.44	0.46

NACA

TABLE II.- FLIGHT-TEST PROGRAM

(a) F-51H and F8F-1 Airplanes

Altitude, ft	A_z	Condition flown by pilot				
		0.40M	0.50M	0.55M	0.60M	0.70M
20,000	2	A,B,C	A,B,C		A,B,C	A,B,C
	3	A,B,C	A,B,C		A,B,C	A,B,C
	4	A,B,C	A,B,C		A,B,C	
10,000	2	A,B,C	A,B,C	A,B,C		
	3	A,B,C	A,B,C	A,B,C		
	4	A,B,C	A,B,C	A,B,C		

(b) F-86A Airplane

Altitude, ft	A_z	Condition flown by pilot				
		0.70M	0.87M	0.90M	0.93M	0.97M
35,000	2	A,B	A	A	A	A
	2-1/2	B	A,B	A,B	A,B	A,B
	3	A,B	A,B	A,B	A,B	A,B
10,000	2	A,B	A,B	A,B		
	3	A,B	A,B	A,B		
	4	A,B	A,B	A,B		
	5	A,B	A,B	A,B		

(c) F-86E Airplane

Altitude, ft	A_z	Condition flown by pilot				
		0.70M	0.87M	0.90M	0.93M	0.97M
35,000	1-1/2	A				
	2	A	A	A,B	A,B	A,B
	2-1/2	A	A	A	A	
	3	B	A,B	A,B	A,B	A,B
	4		B			A,B
10,000	2	A,B	A,B	A,B		
	3	A,B	A,B	A,B		
	4	A,B	A,B	A,B		
	5	A,B	A,B	A,B		

TABLE III.- PILOT LEARNING ON F-86E AIRPLANE

Altitude, ft	M	A_z	Flight	Run	Aim wander: Straight flight σ_x mils	Aim wander: Straight flight σ_y mils	Aim wander: Turning flight σ_x mils	Aim wander: Turning flight σ_y mils
35,000	0.70	2.5	8	3	1.9	2.3	3.8	4.5
			19	4	---	---	3.5	3.6
	.87	2.0	7	8	.9	.8	2.3	1.9
			16	1	1.2	1.6	3.8	3.2
10,000	.70	2.0	6	5	1.5	1.4	1.6	1.6
			19	6	1.2	1.5	1.8	1.8
		3.0	6	6	1.8	1.3	1.8	2.5
			19	7	1.3	1.3	2.8	2.4
		5.0	6	4	1.5	.7	2.7	4.4
			19	9	1.2	1.1	2.9	5.4

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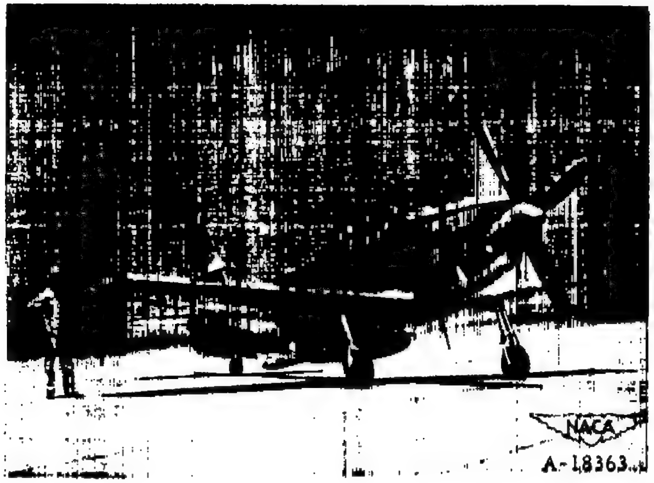
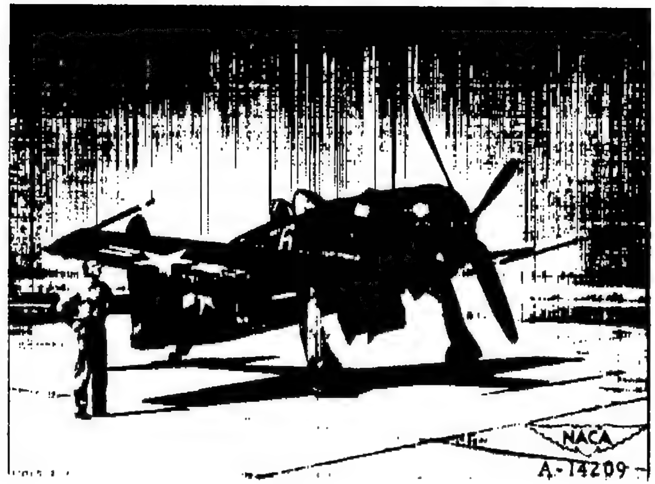
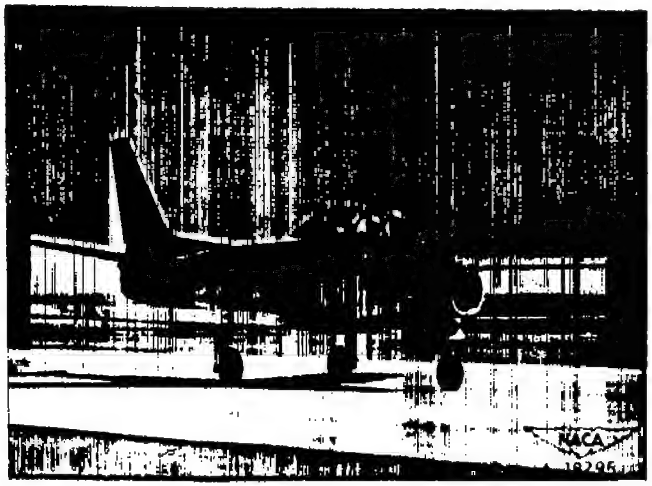


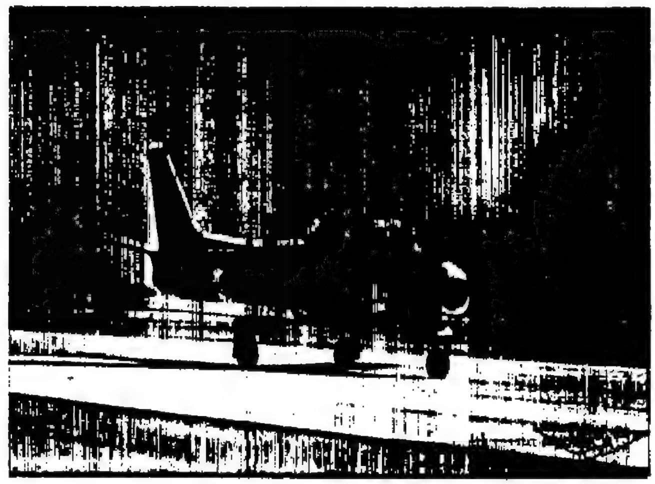
(a) The F-51H airplane.



(b) The F8F-1 airplane.



(c) The F-86A airplane.



(d) The F-86E airplane.

Figure 1.- The four test airplanes.

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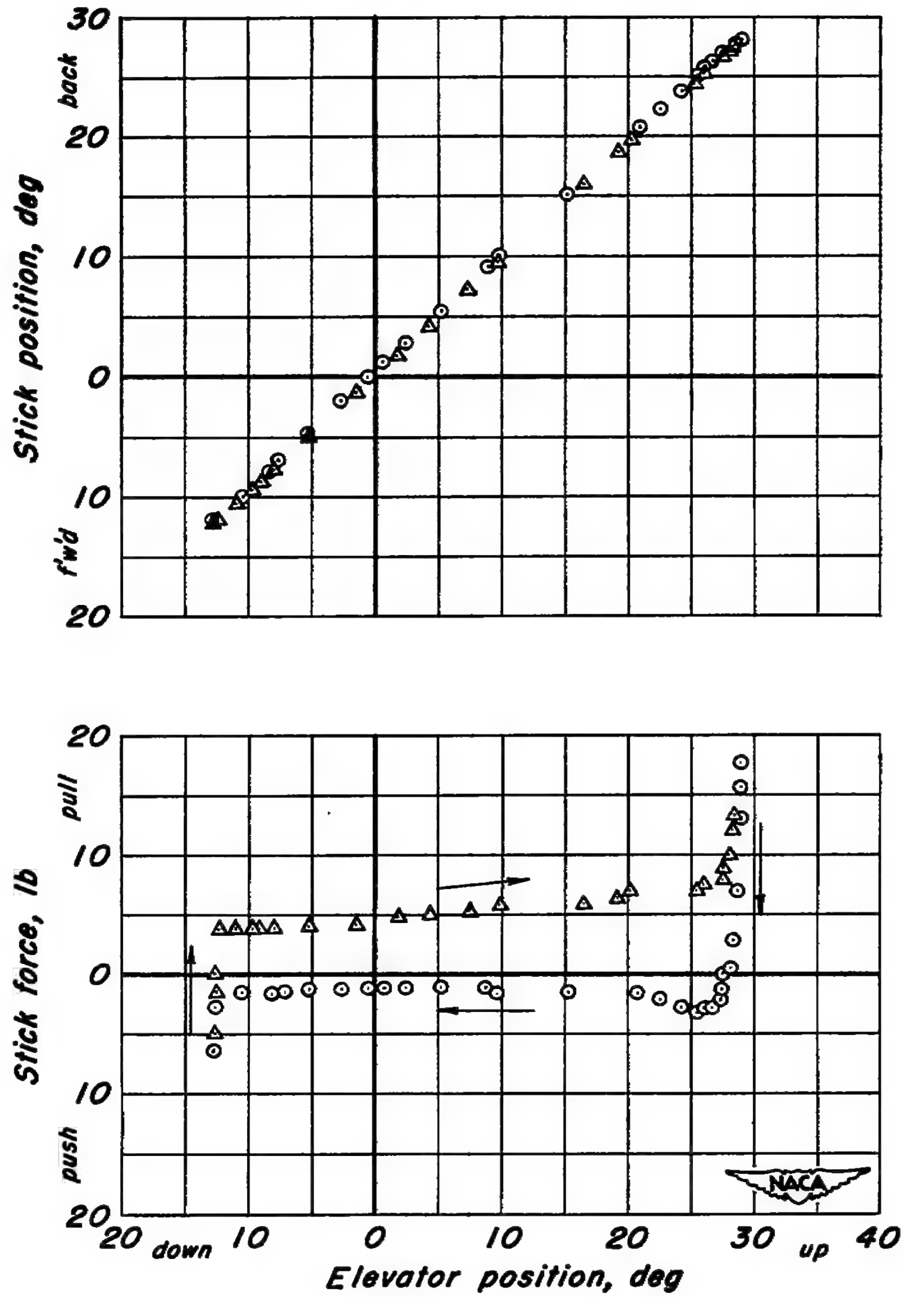

(a) F-86A airplane.

Figure 2.— Ground-friction check, stick-force and stick-gearing characteristics for the longitudinal-control systems of the F-86A and E airplanes.

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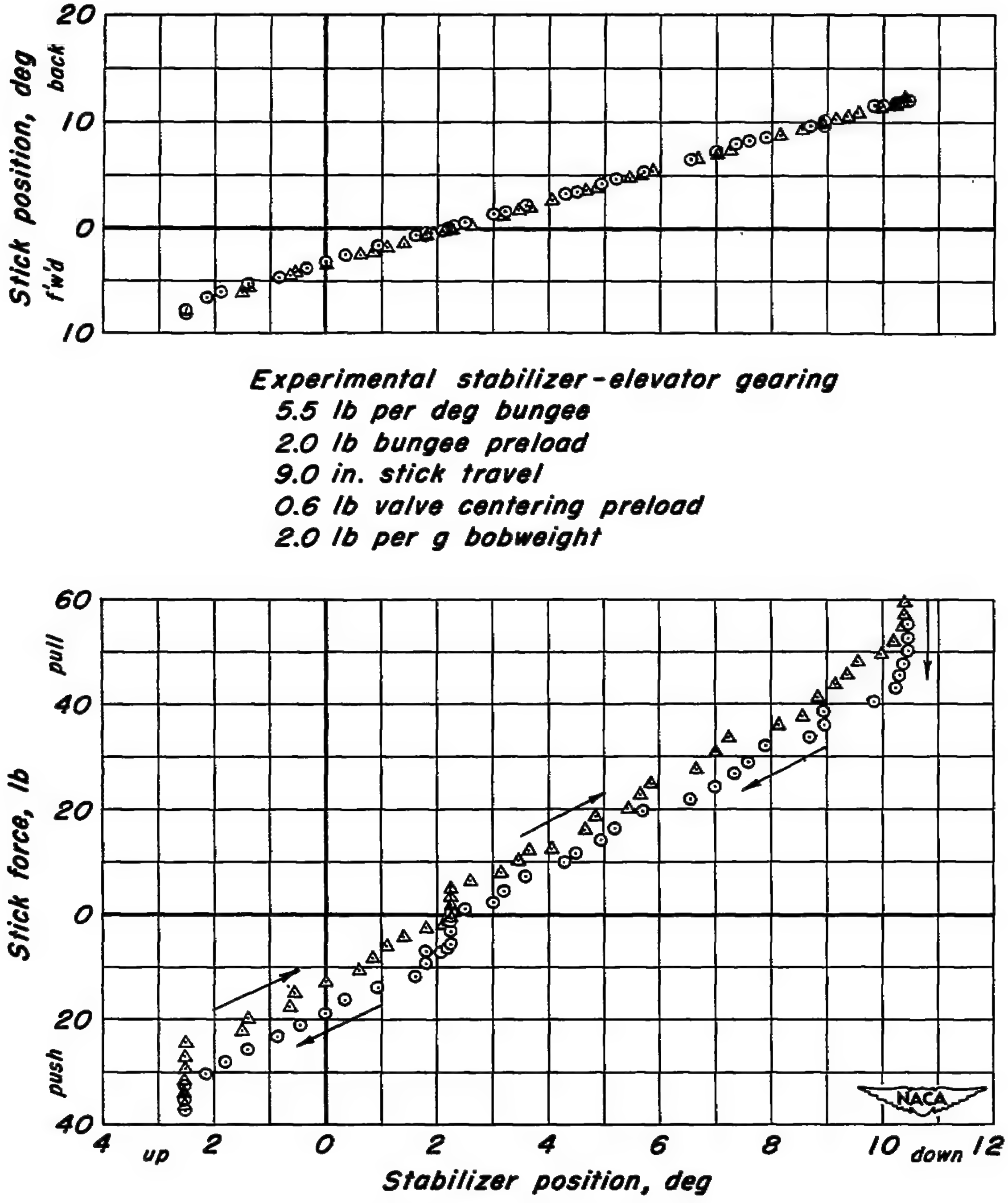

(b) F-86E airplane.

Figure 2.—Concluded.

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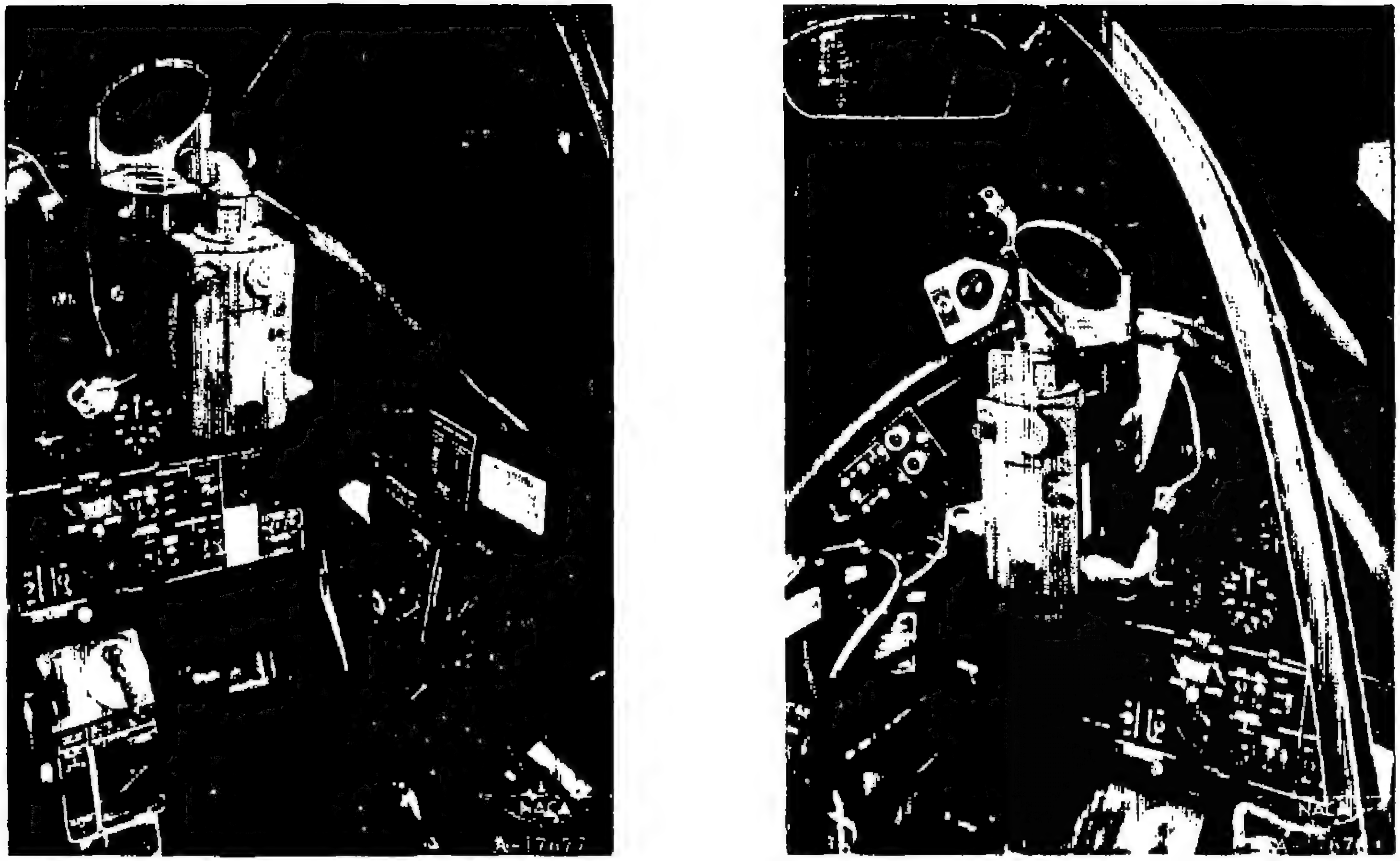

(a) Left-hand view. (b) Right-hand view.

Figure 3.- Typical gunsight and camera installation in cockpit of tracking airplane.

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Figure 4.- Pilot's view through gunsight showing reticle image and target airplane.

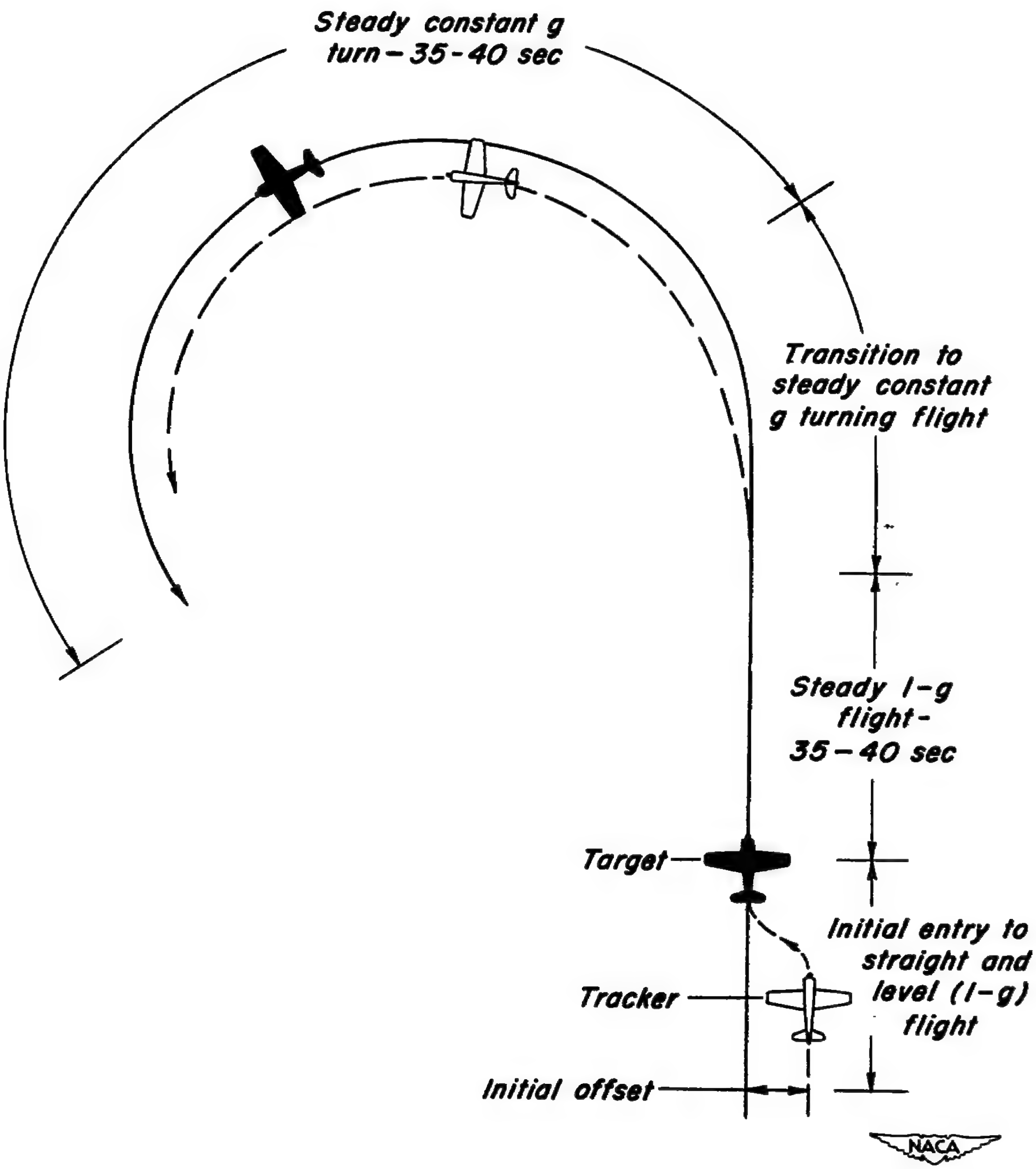


Figure 5.– Plan view of standardized test maneuver.

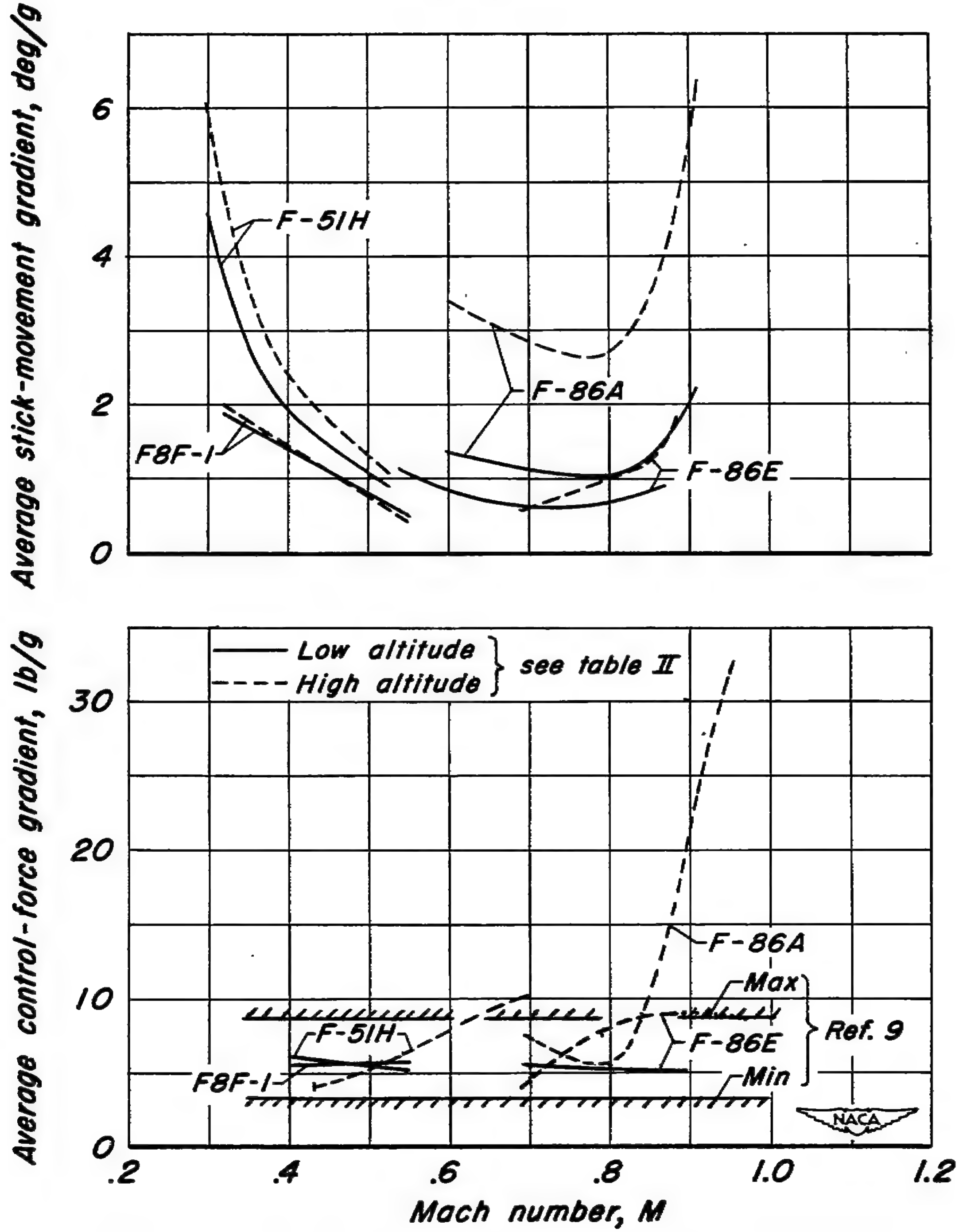


Figure 6.– Average control-force and stick-movement gradients with normal acceleration for the flight conditions covered by the tracking tests.

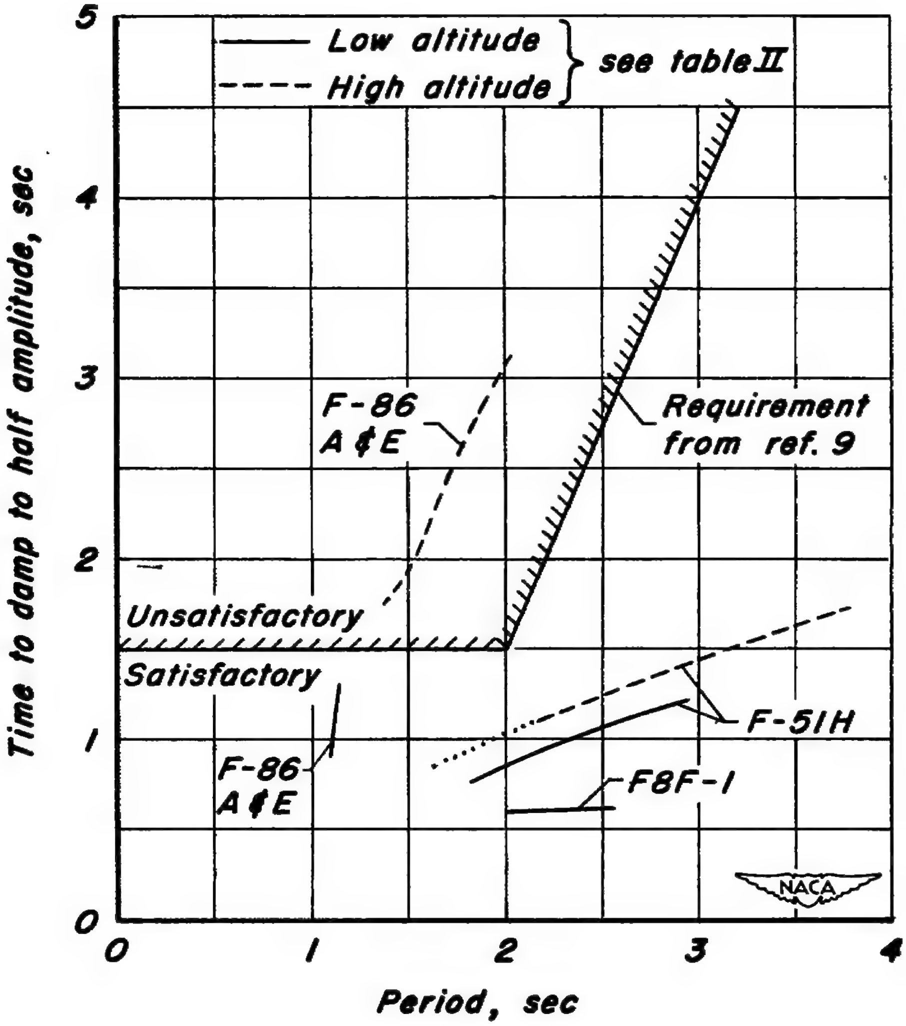


Figure 7.– The range of lateral-directional oscillatory characteristics included in the tracking tests.

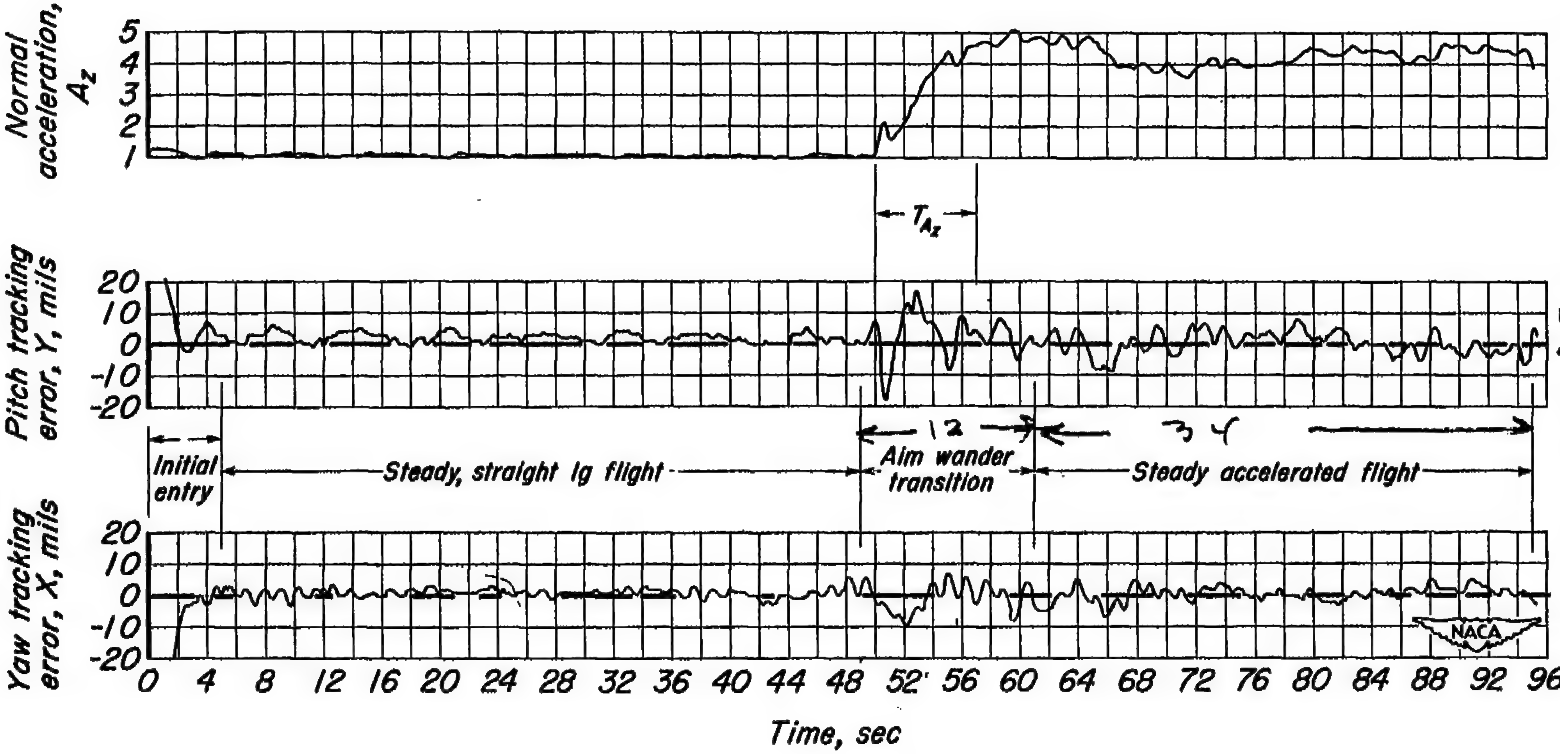


Figure 8.— Time history of aim errors and normal acceleration factor in a typical gunnery run.

the data portion of these assumed
$\frac{4}{1} = 4$ ... of flight occurs in the transition region

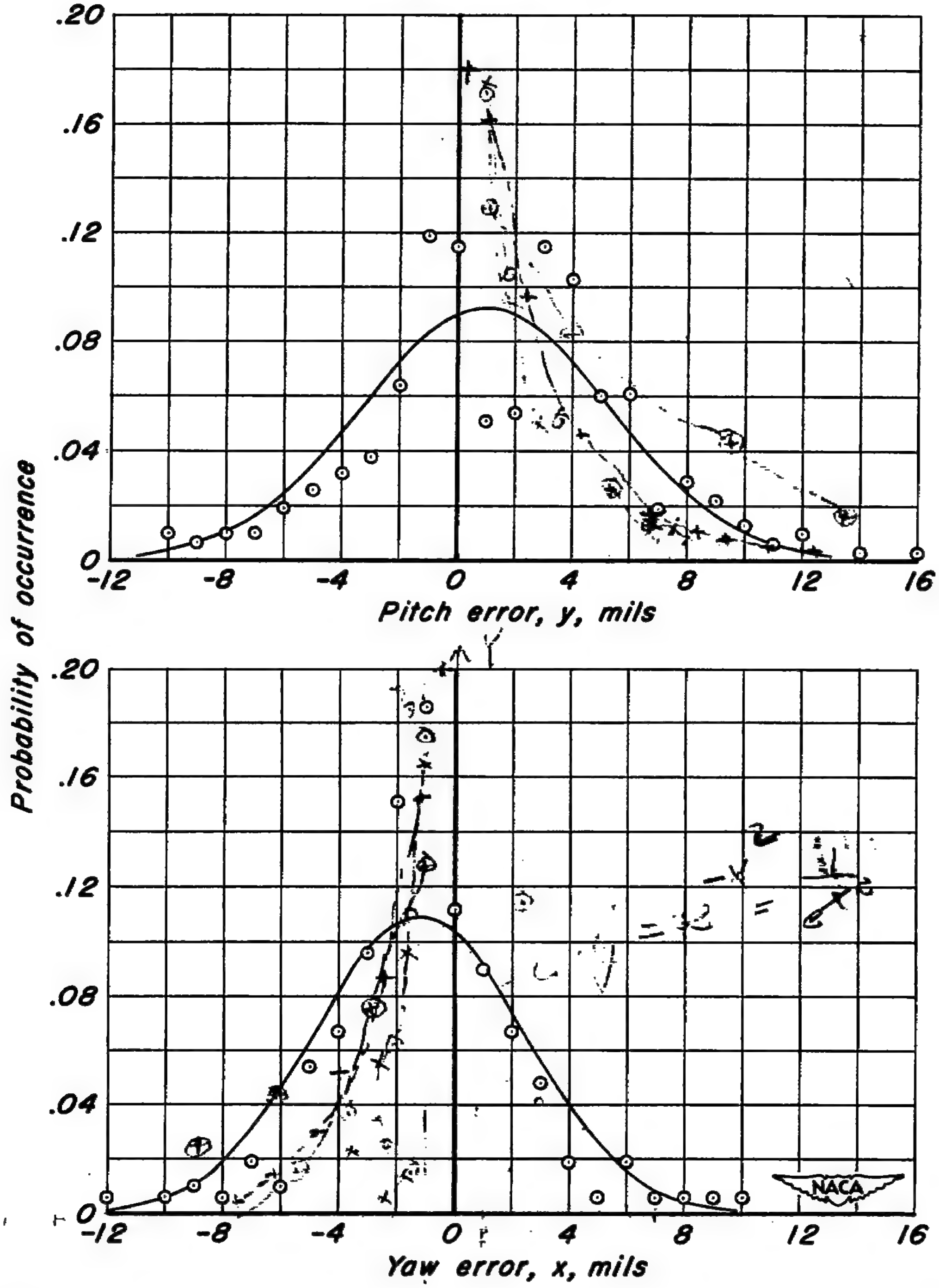
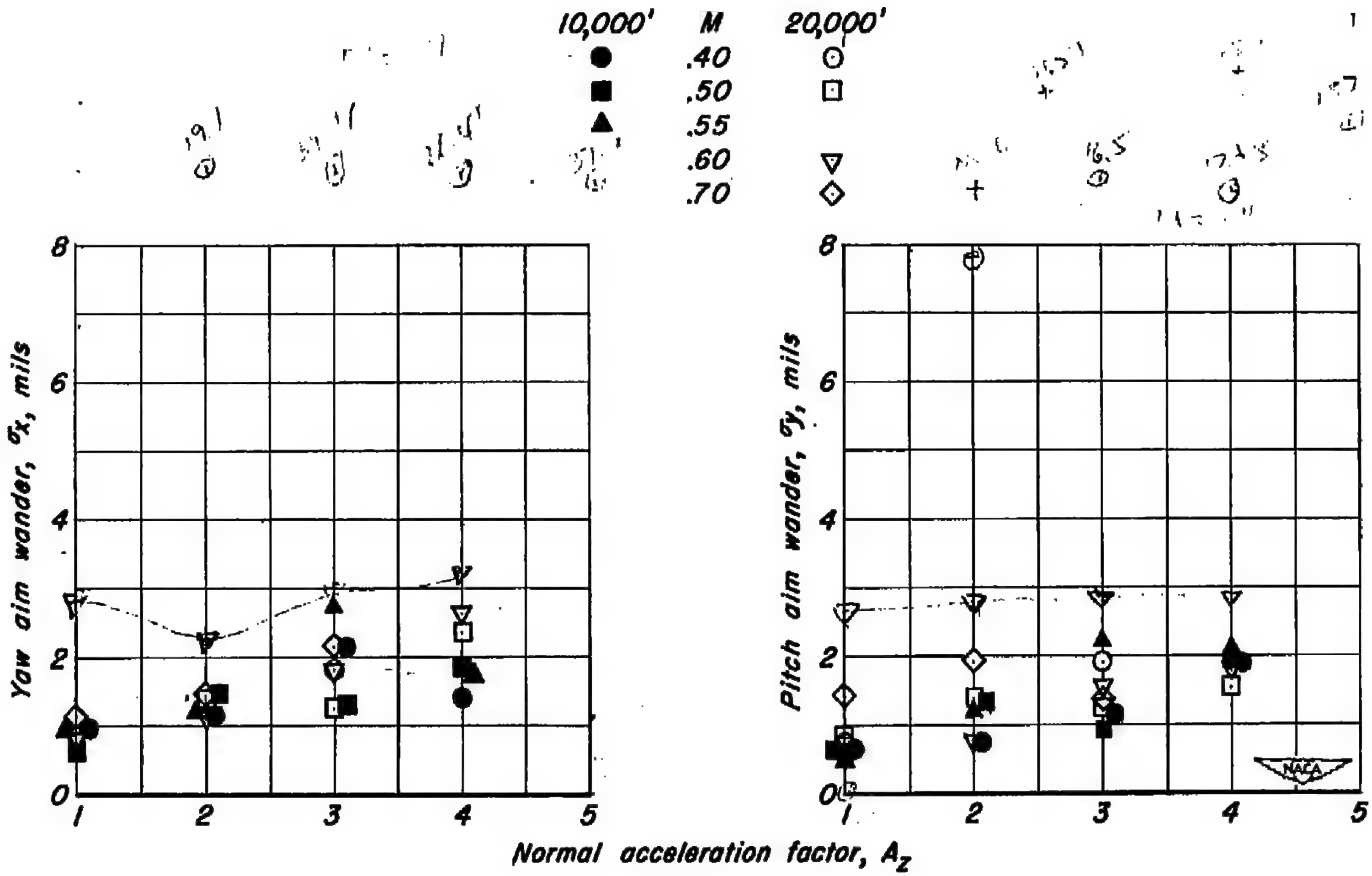


Figure 9.— Typical probability distribution of aim wander in comparison with Gaussian distribution curve.



(a) Pilot A.

Figure 10.– Aim wander under steady-state conditions, F-51H airplane.

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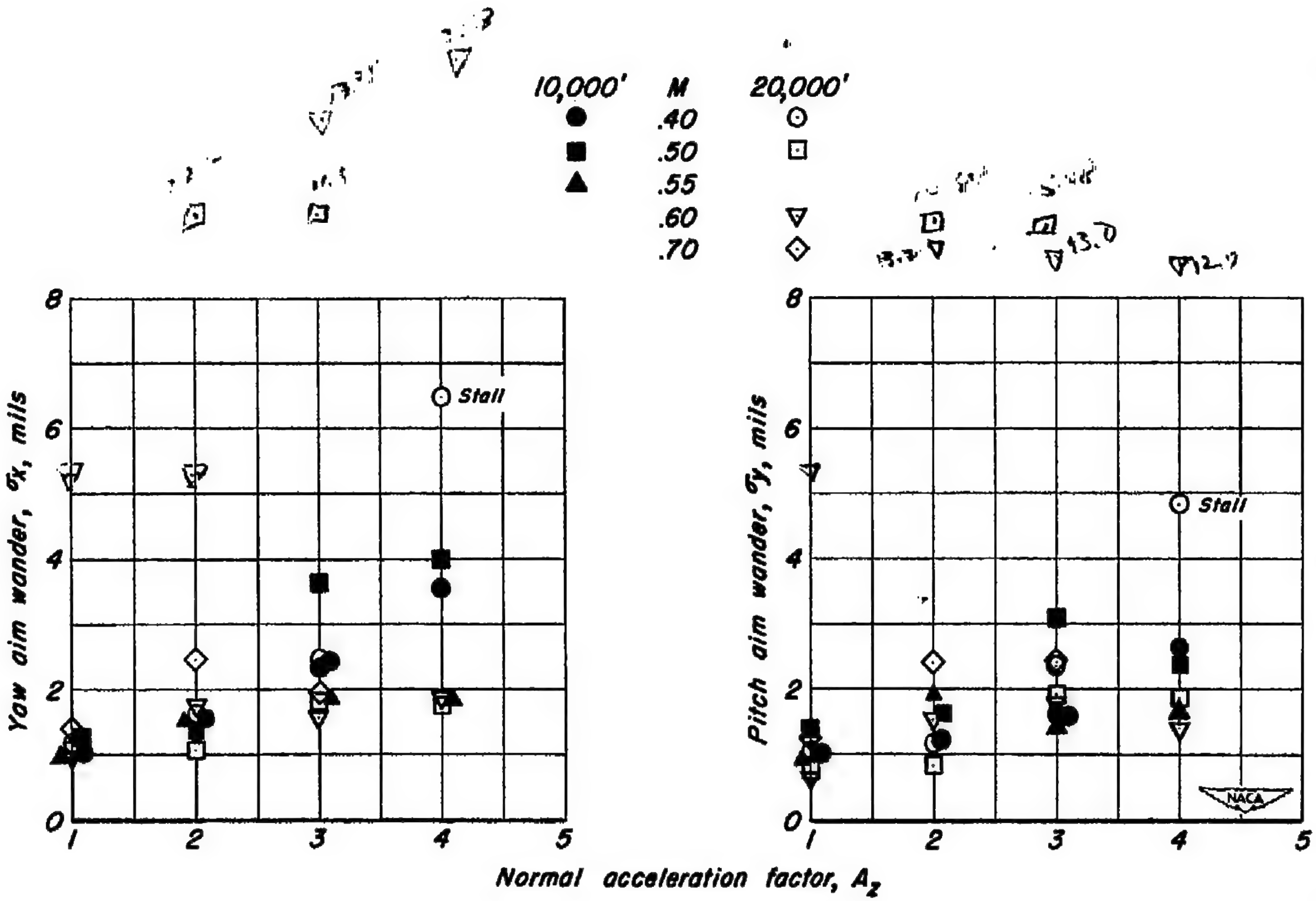

(b) Pilot B.

Figure 10.– Continued.

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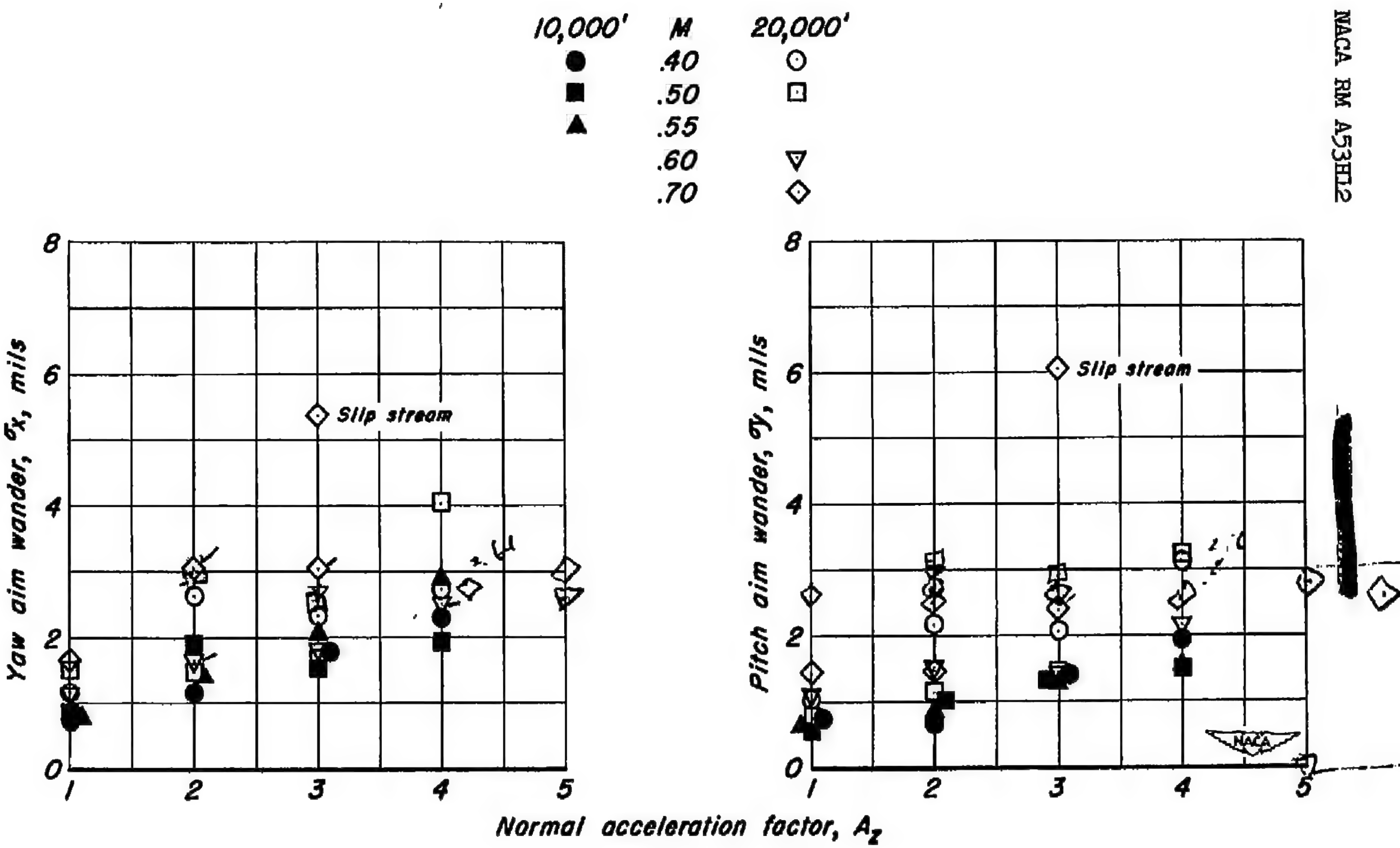

(c) Pilot C.

Figure 10.— Concluded.

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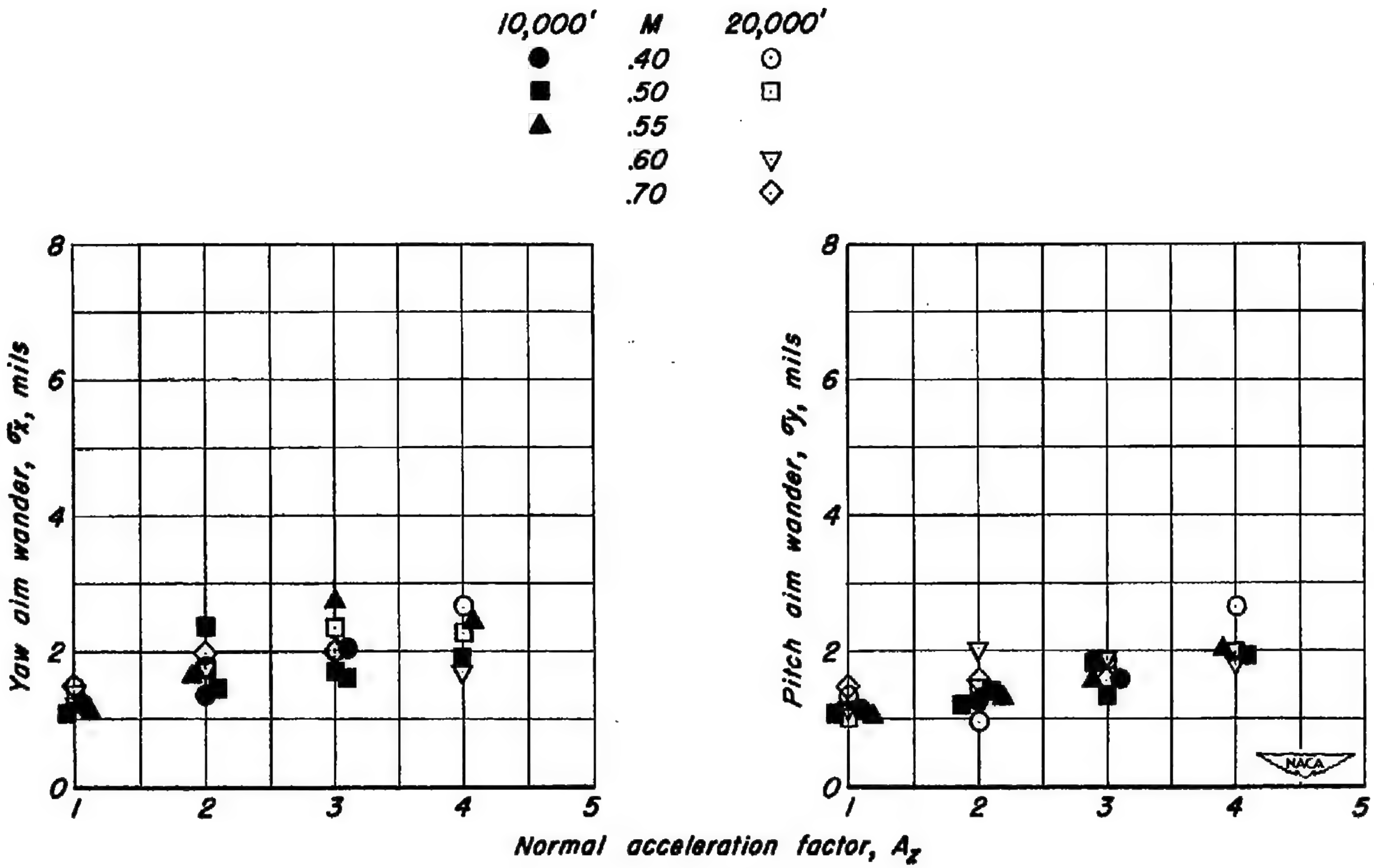

(a) Pilot A.

Figure 11.— Aim wander under steady-state conditions, F8F-1 airplane.

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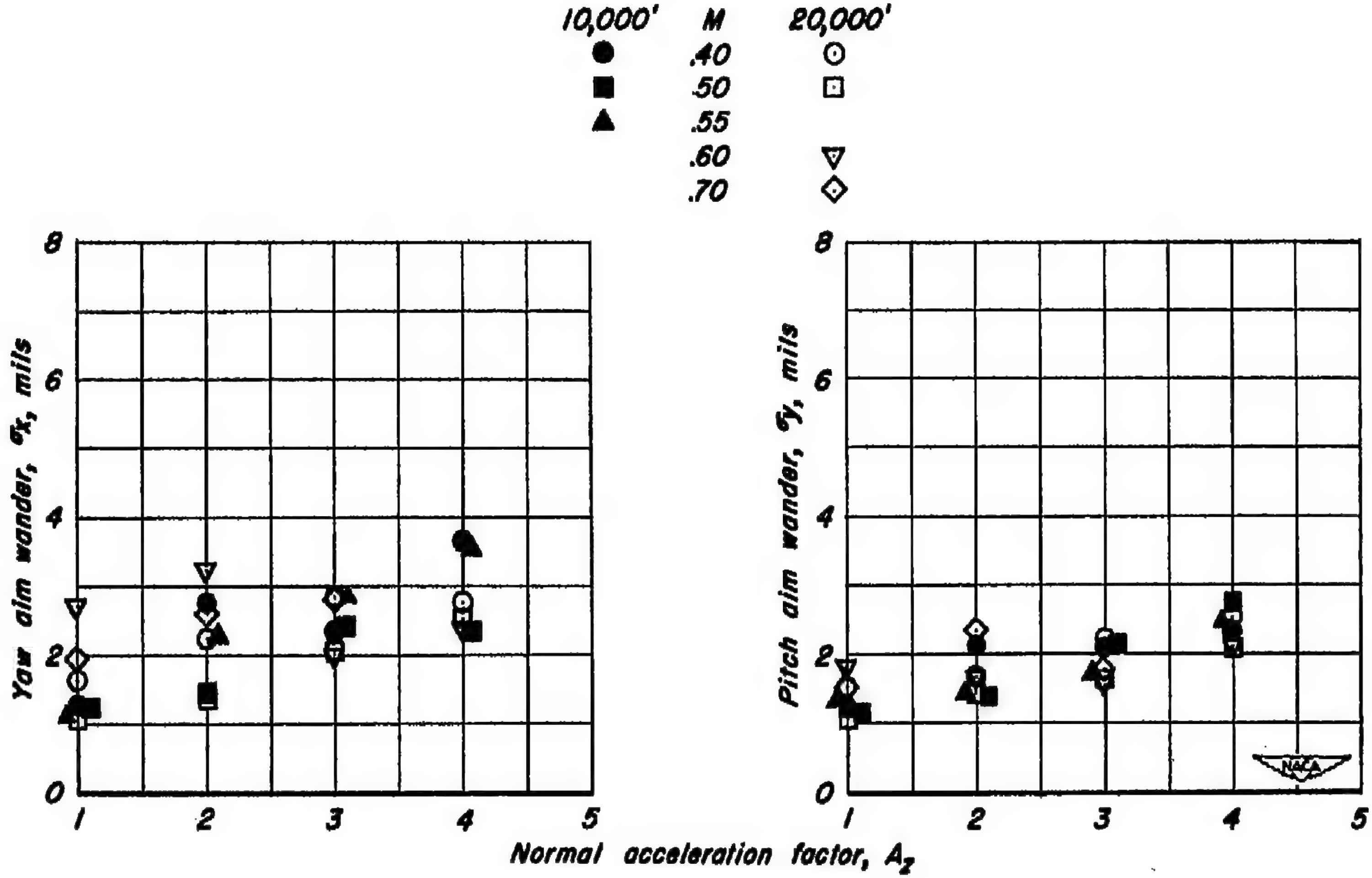
[redacted]



(b) Pilot B.

Figure 11.— Continued.

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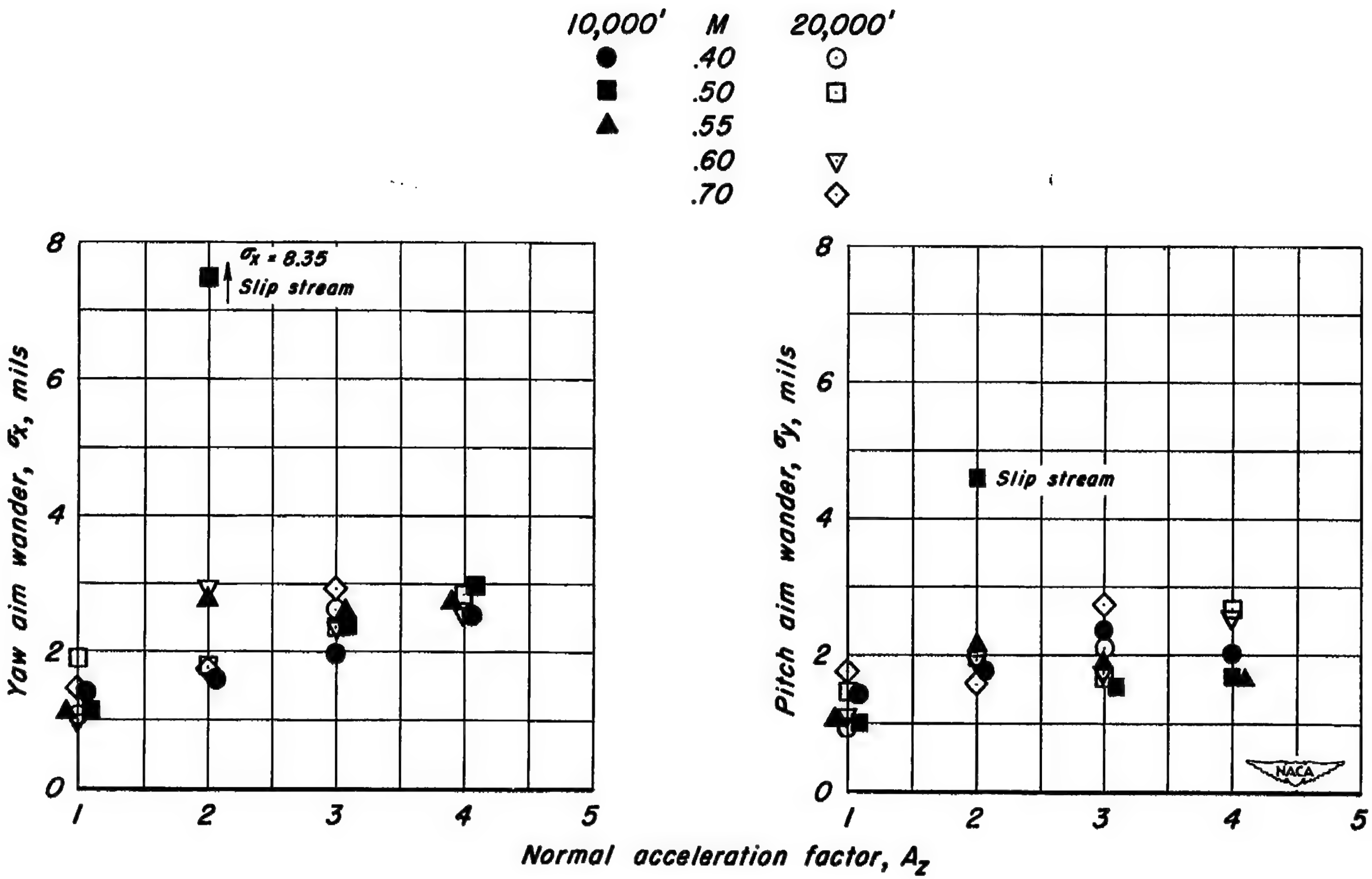
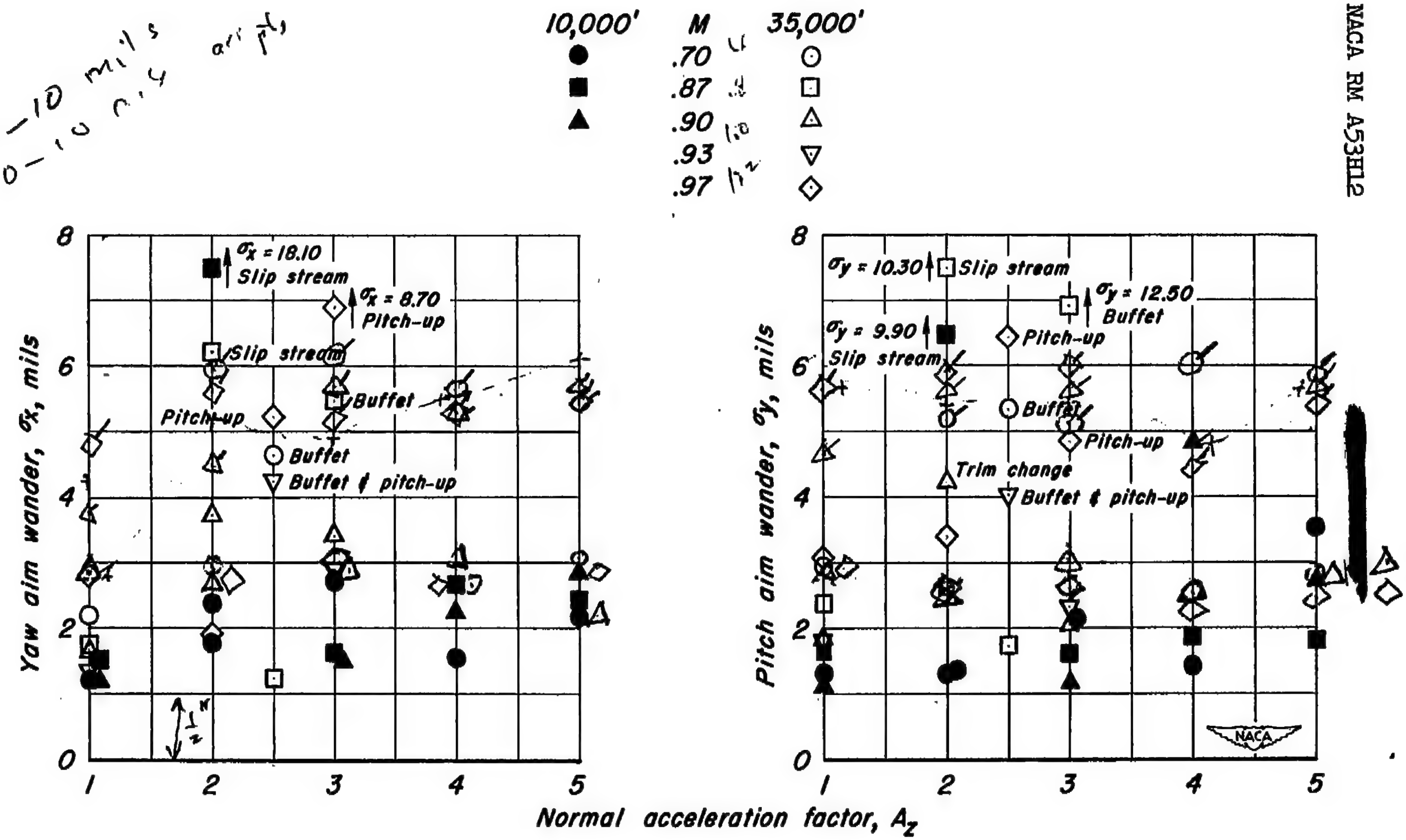


(c) Pilot C.

Figure 11.—Concluded.

[redacted]

0–10 mils all pts,
0–10 mils



[redacted]

[redacted]

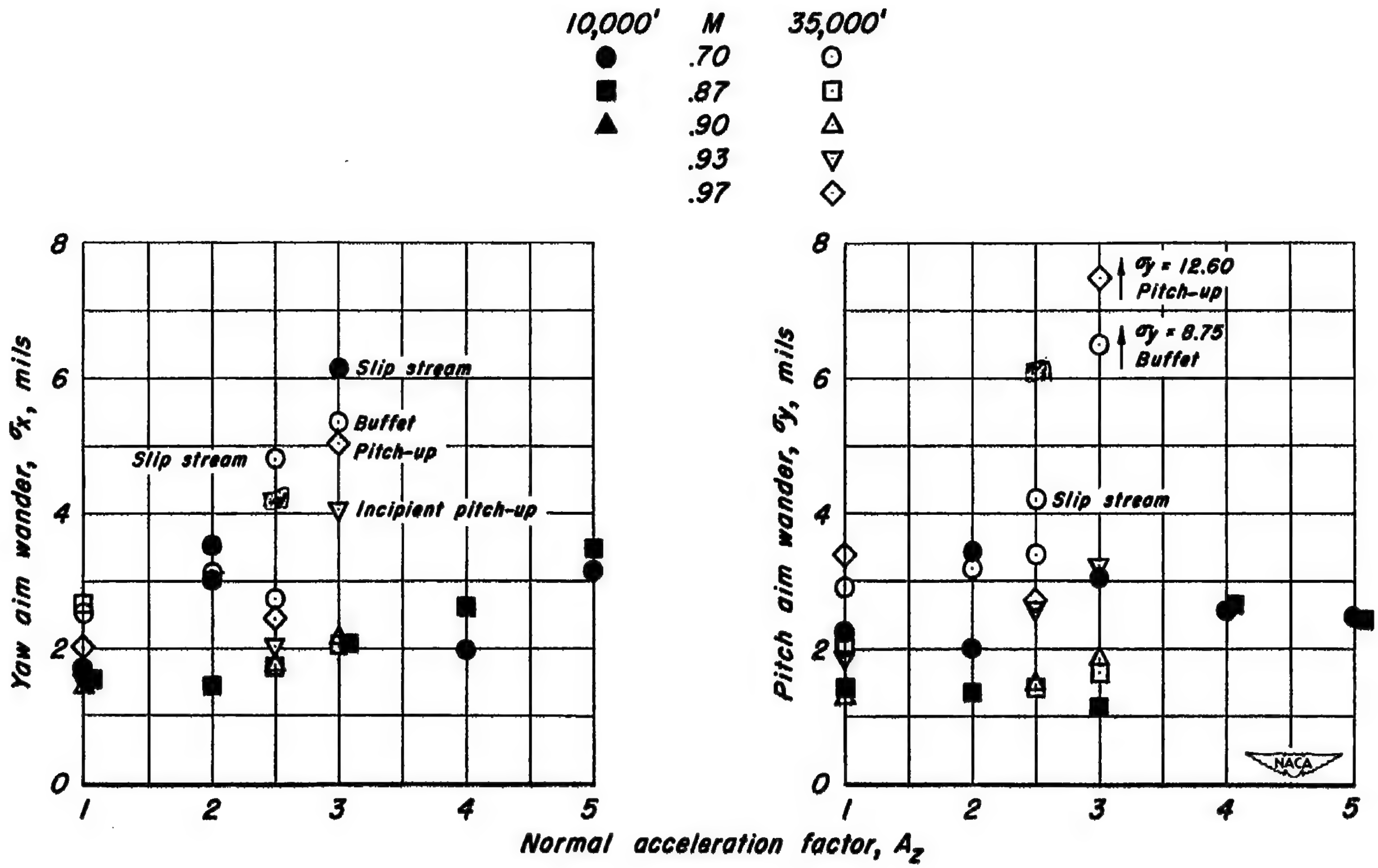
(a) Pilot A.

0–10 range
light turn
constant H
absolute value

Figure 12.— Aim wander under steady-state conditions, F-86A airplane.

Practically no effect of 'G' range and altitude on result

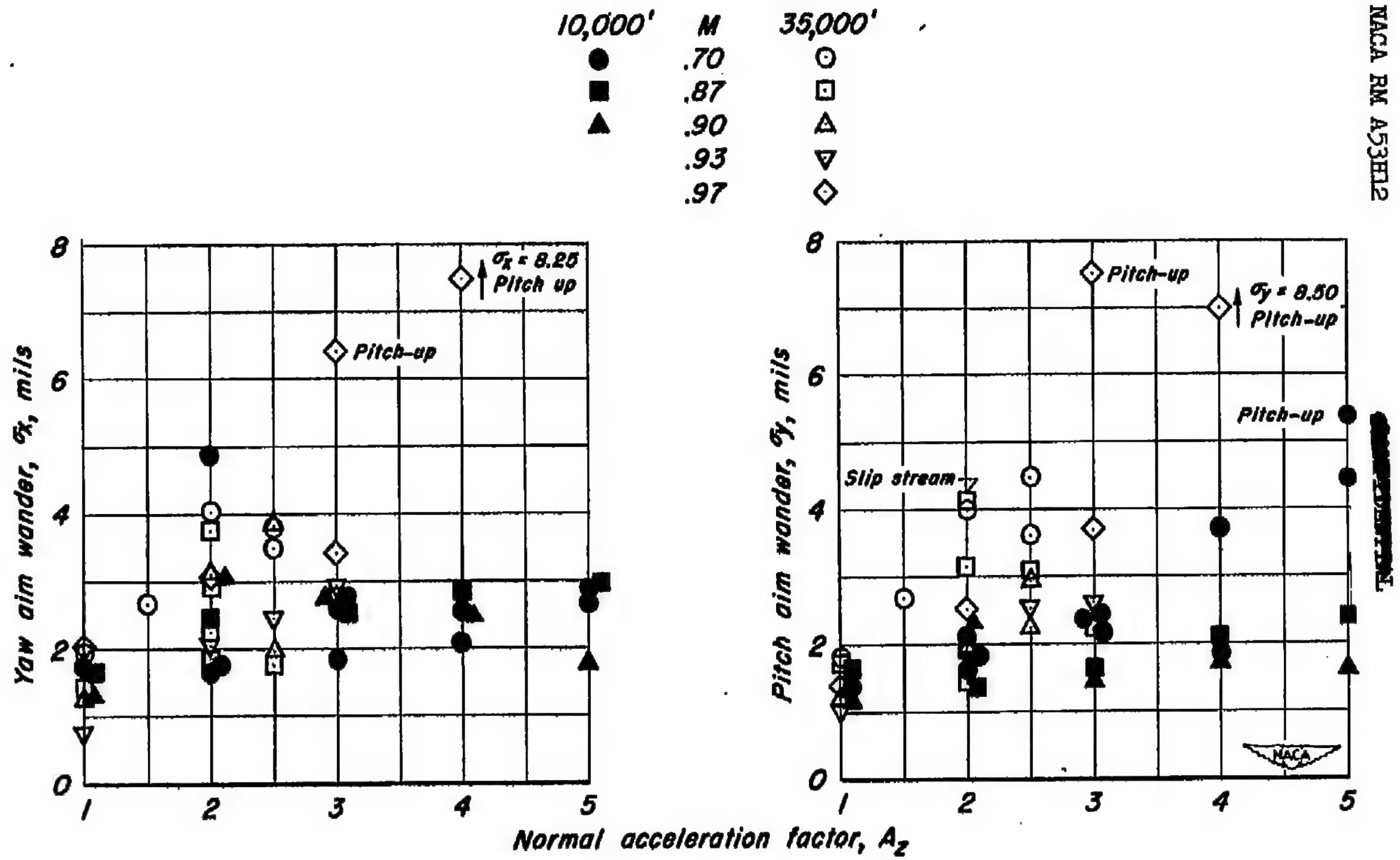
[redacted]



(b) Pilot B.

Figure 12.— Concluded.

[redacted]



[redacted]

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(a) Pilot A.

Figure 13.— Aim wander under steady-state conditions, F-86E airplane.

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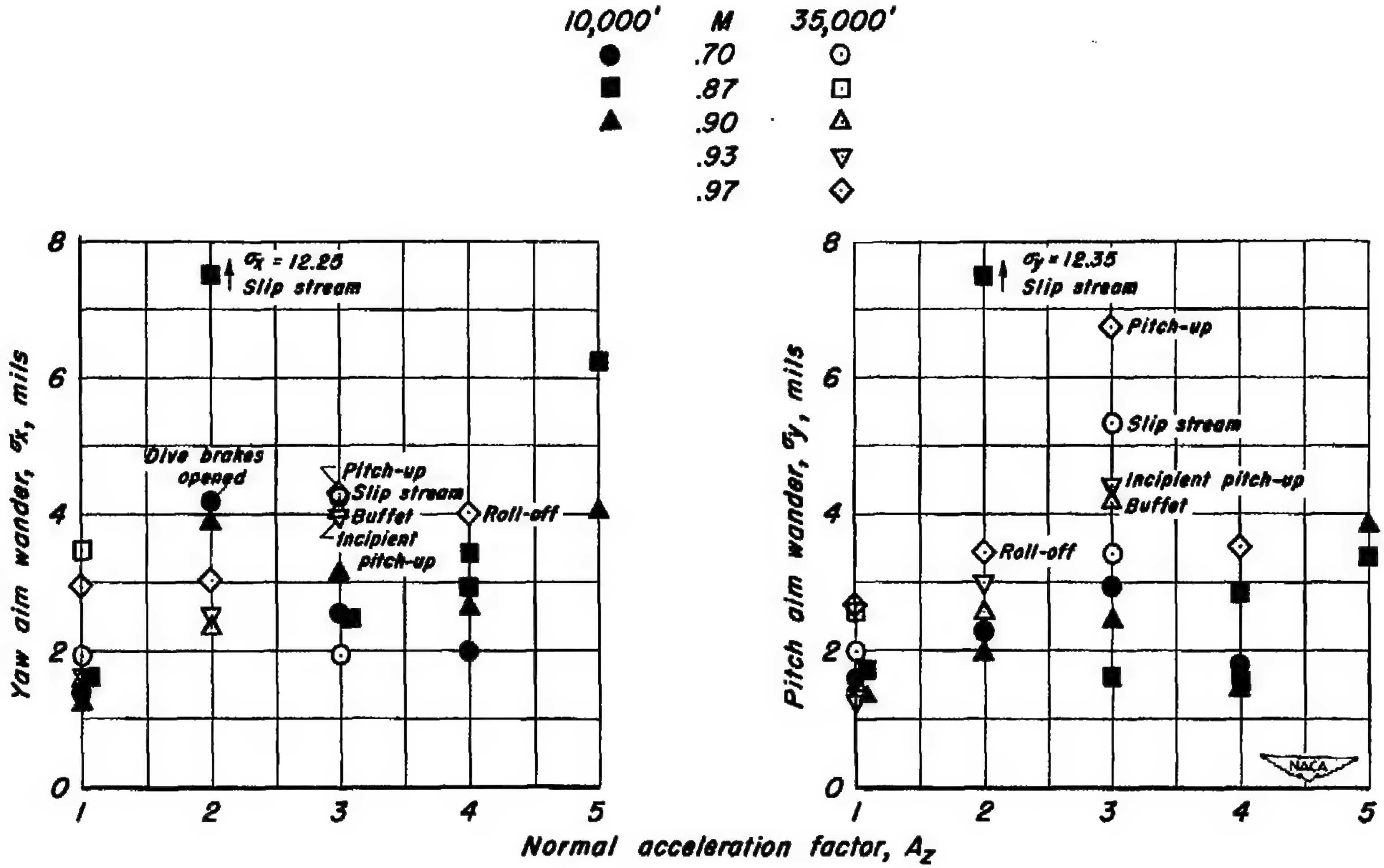

(b) Pilot B.

Figure 13.— Concluded.

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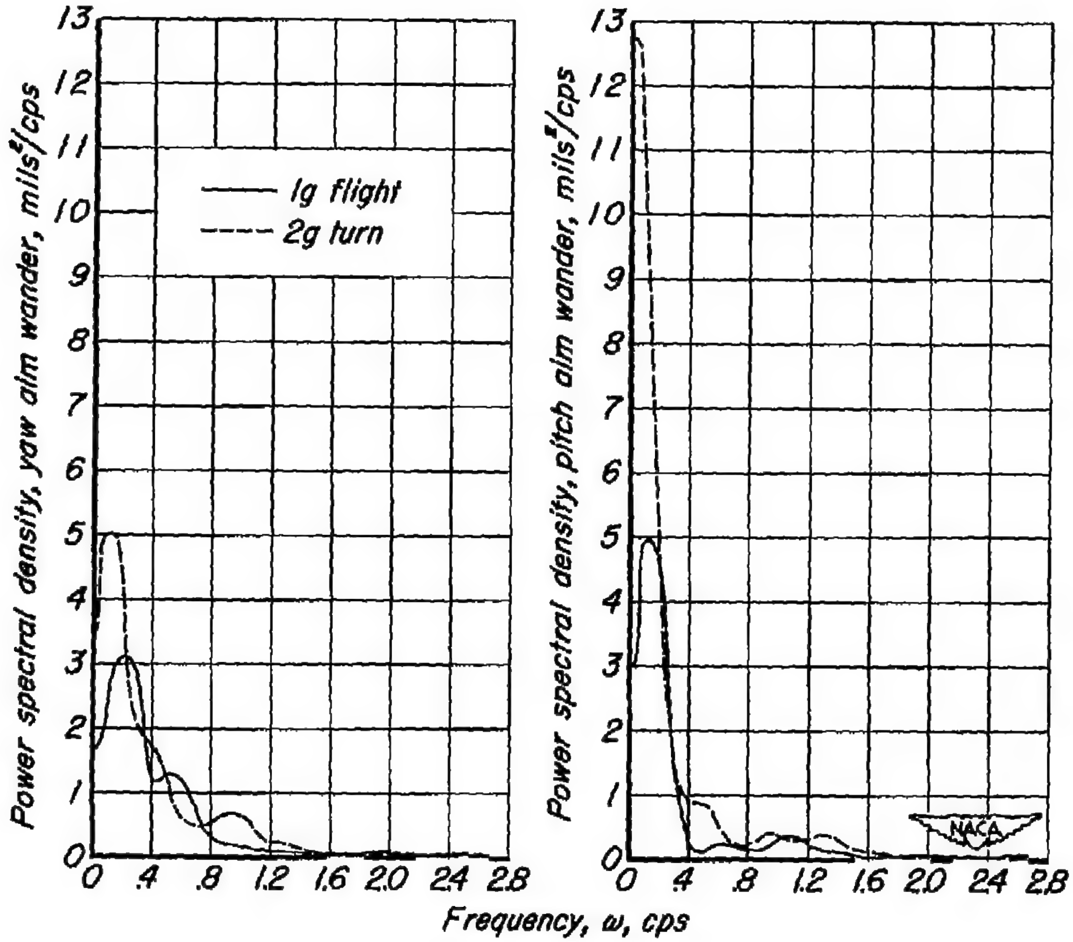
[redacted]



(a) Aim wander.

Figure 14.—Typical power spectral densities of aim wander and control-surface motions for the F-51H airplane under steady-state conditions, Mach number 0.70, 20,000 feet.

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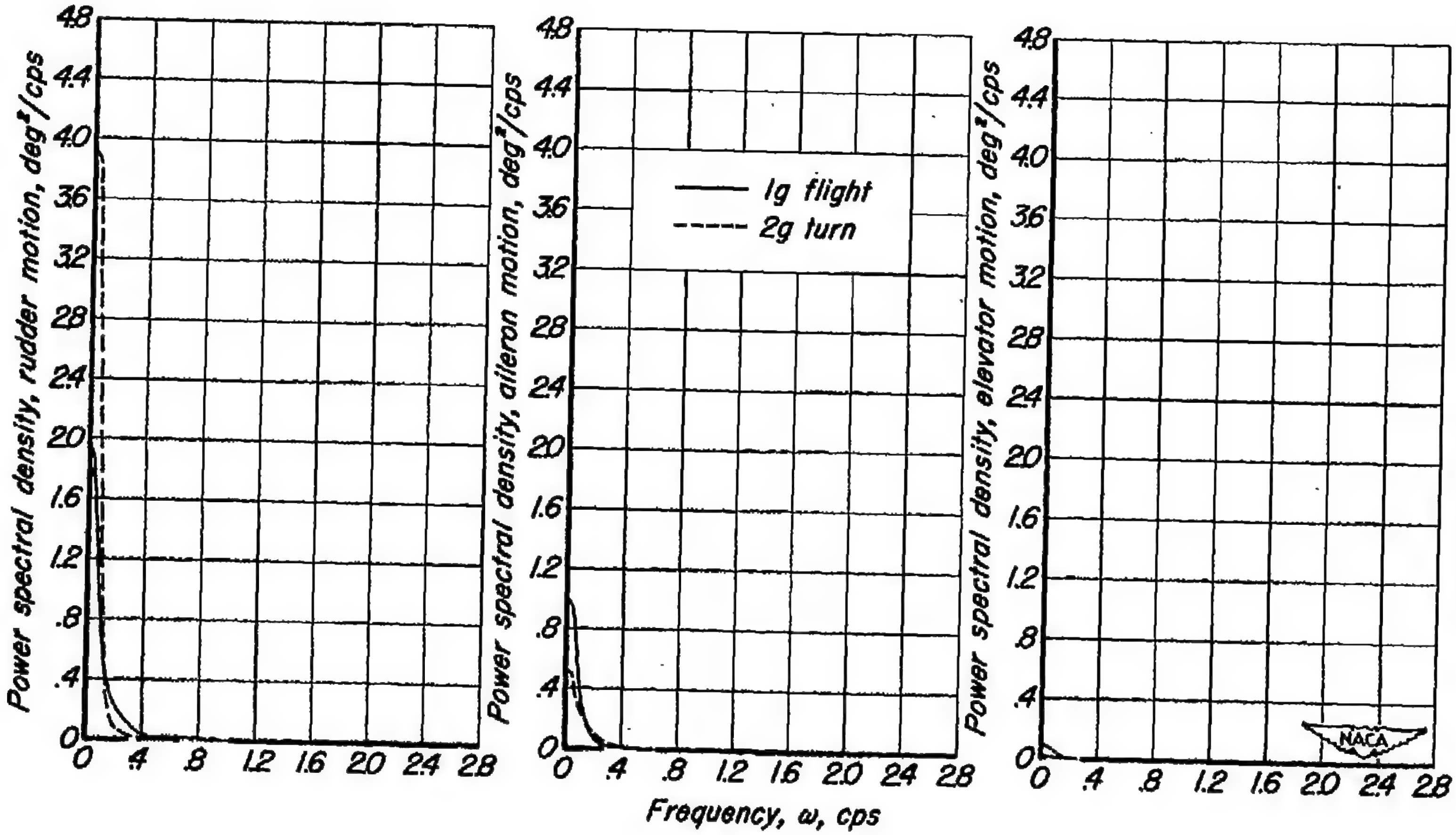
[redacted]

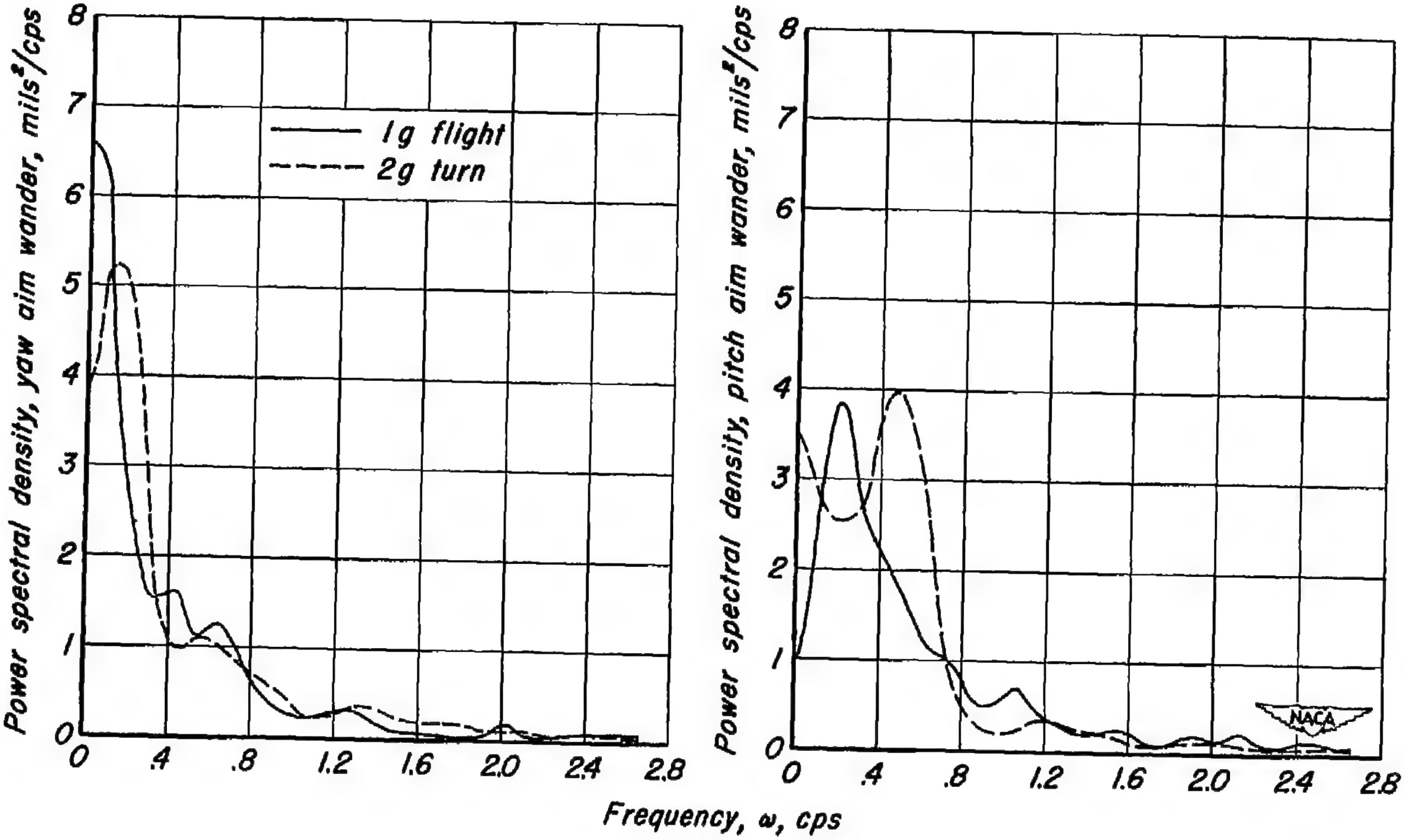


(b) Control-surface motions.

Figure 14.—Concluded.

[redacted]

[redacted]

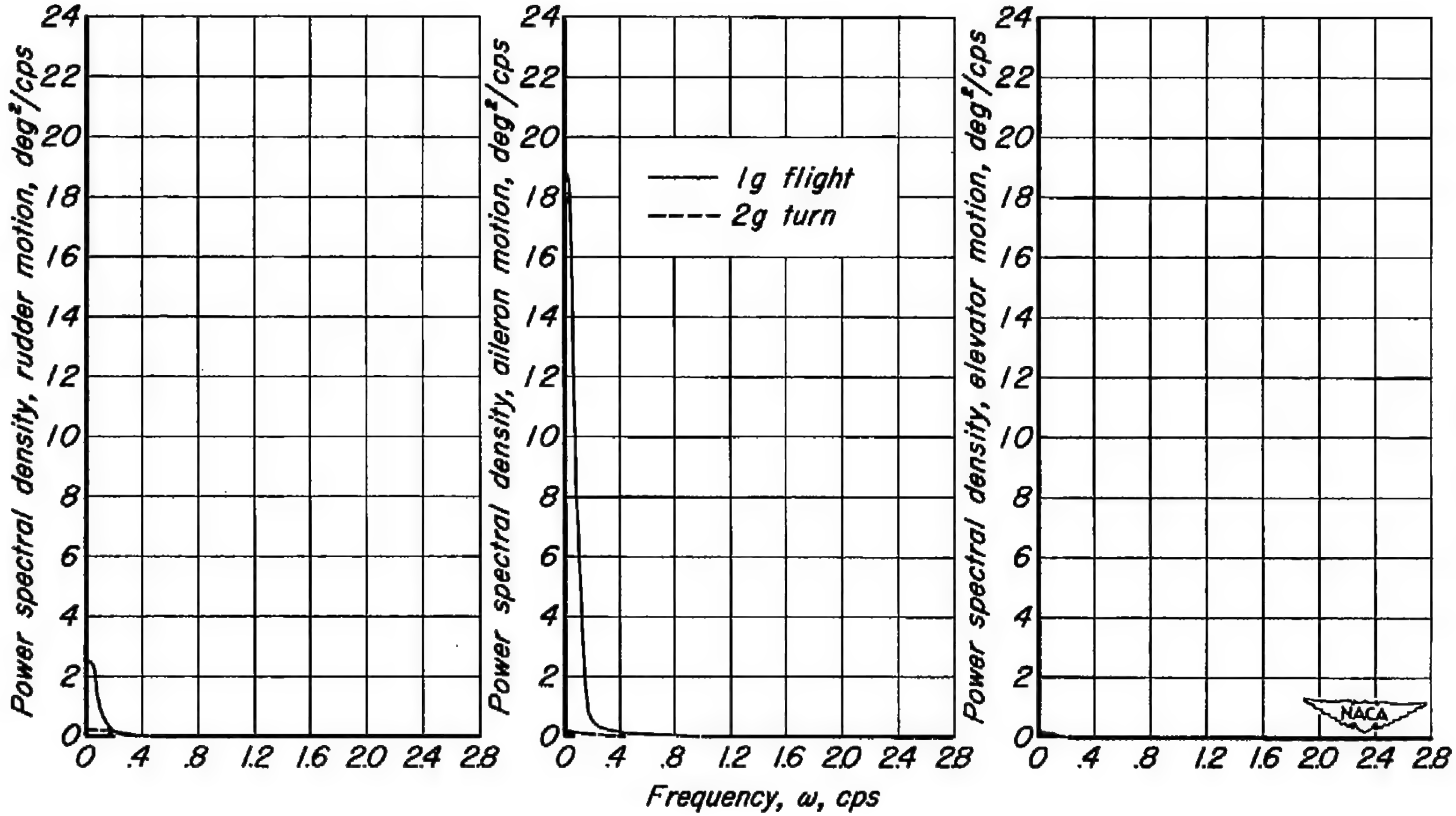


(a) Aim wander.

Figure 15.– Typical power spectral densities of aim wander and control-surface motions for the F8F-1 airplane under steady-state conditions, Mach number 0.70, 20,000 feet.

[redacted]

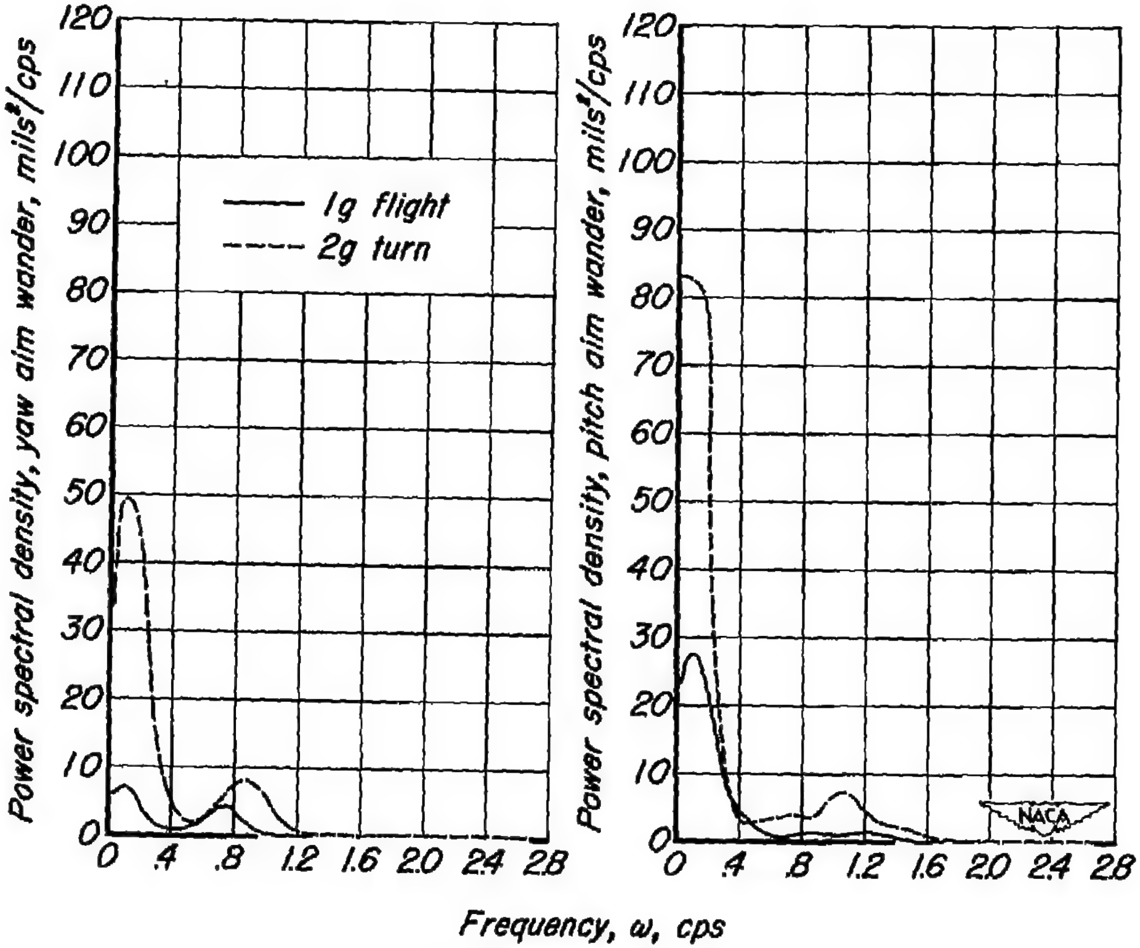
[redacted]



(b) Control-surface motions.

Figure 15.—Concluded.

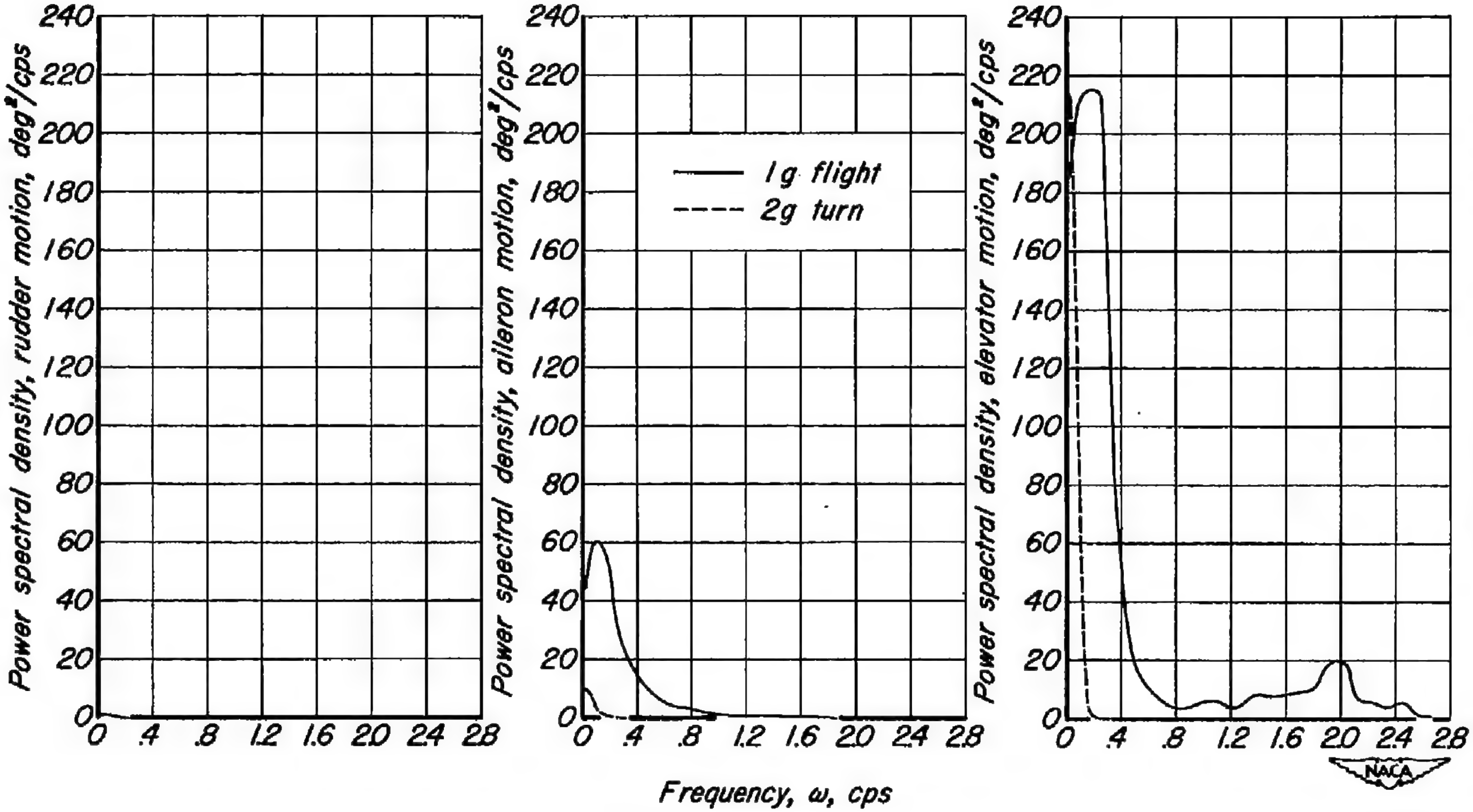
[redacted]



(a) Aim wander.

Figure 16.—Typical power spectral densities of aim wander and control-surface motions for the F-86A airplane under steady-state conditions, Mach number 0.93, 35,000 feet.

[redacted]

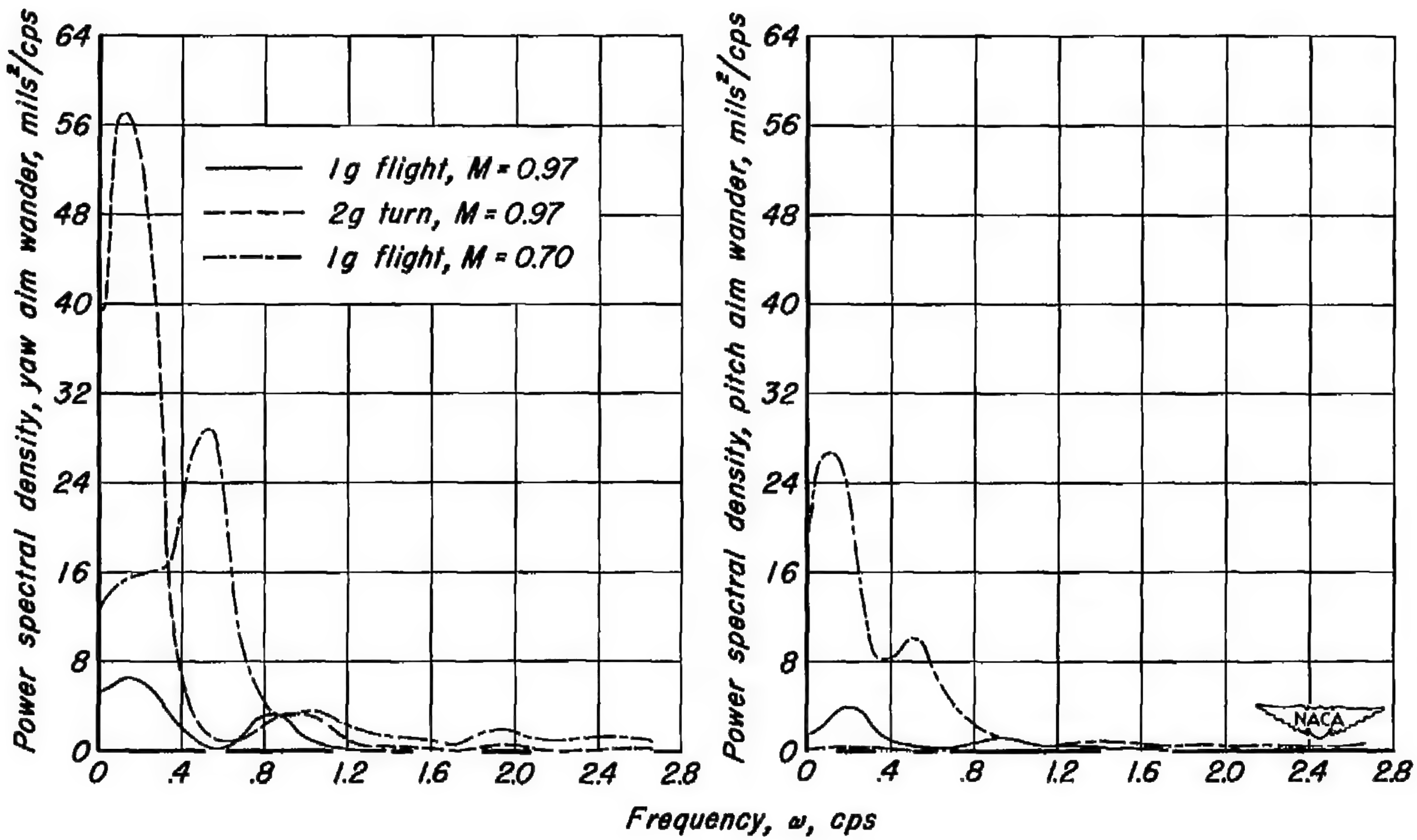


(b) Control-surface motions.

Figure 16.— Concluded.

[redacted]

[redacted]

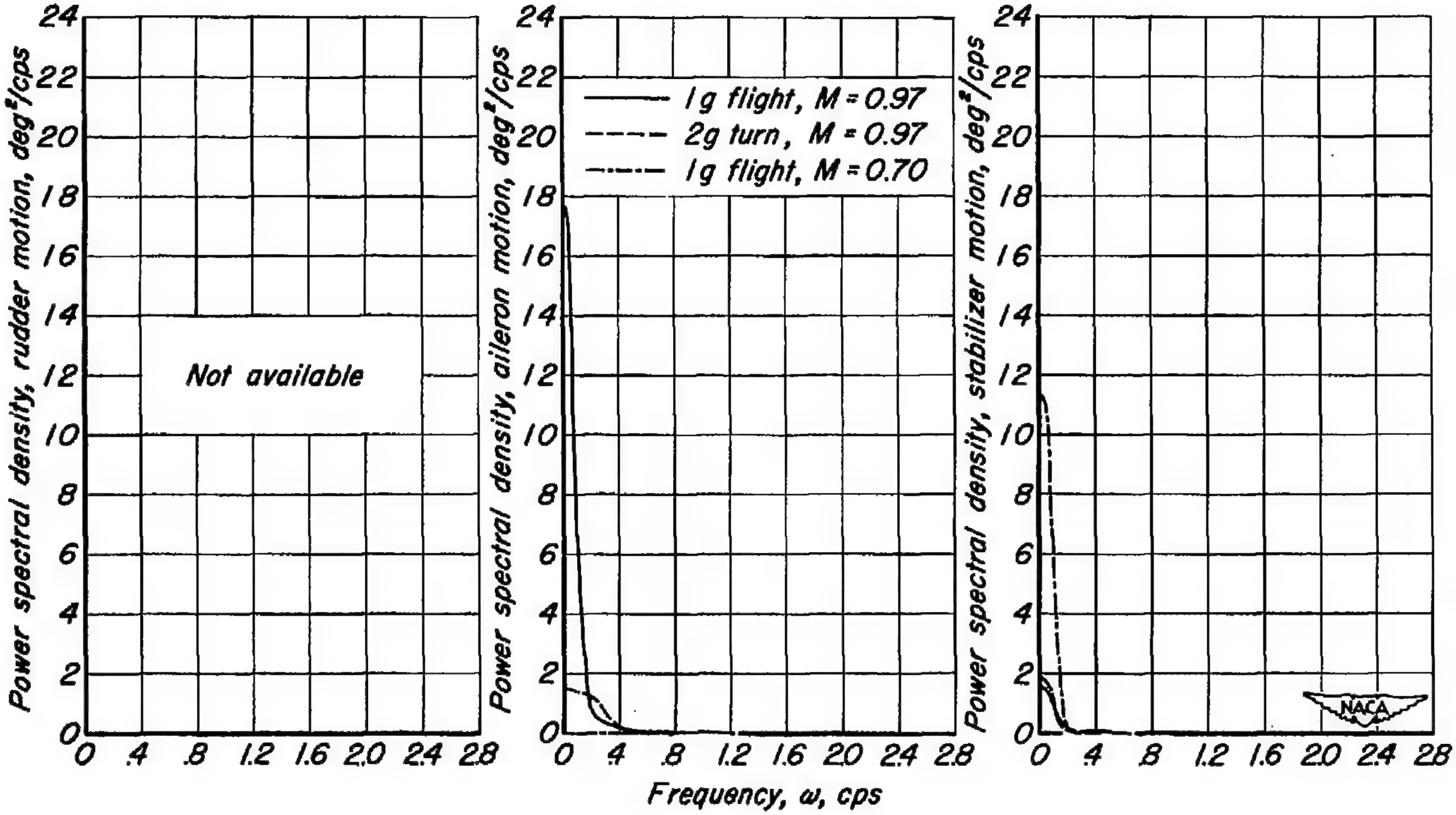


(a) Aim wander.

Figure 17.– Typical power spectral densities of aim wander and control-surface motions for the F-86E airplane under steady-state conditions, 35,000 feet.

[redacted]

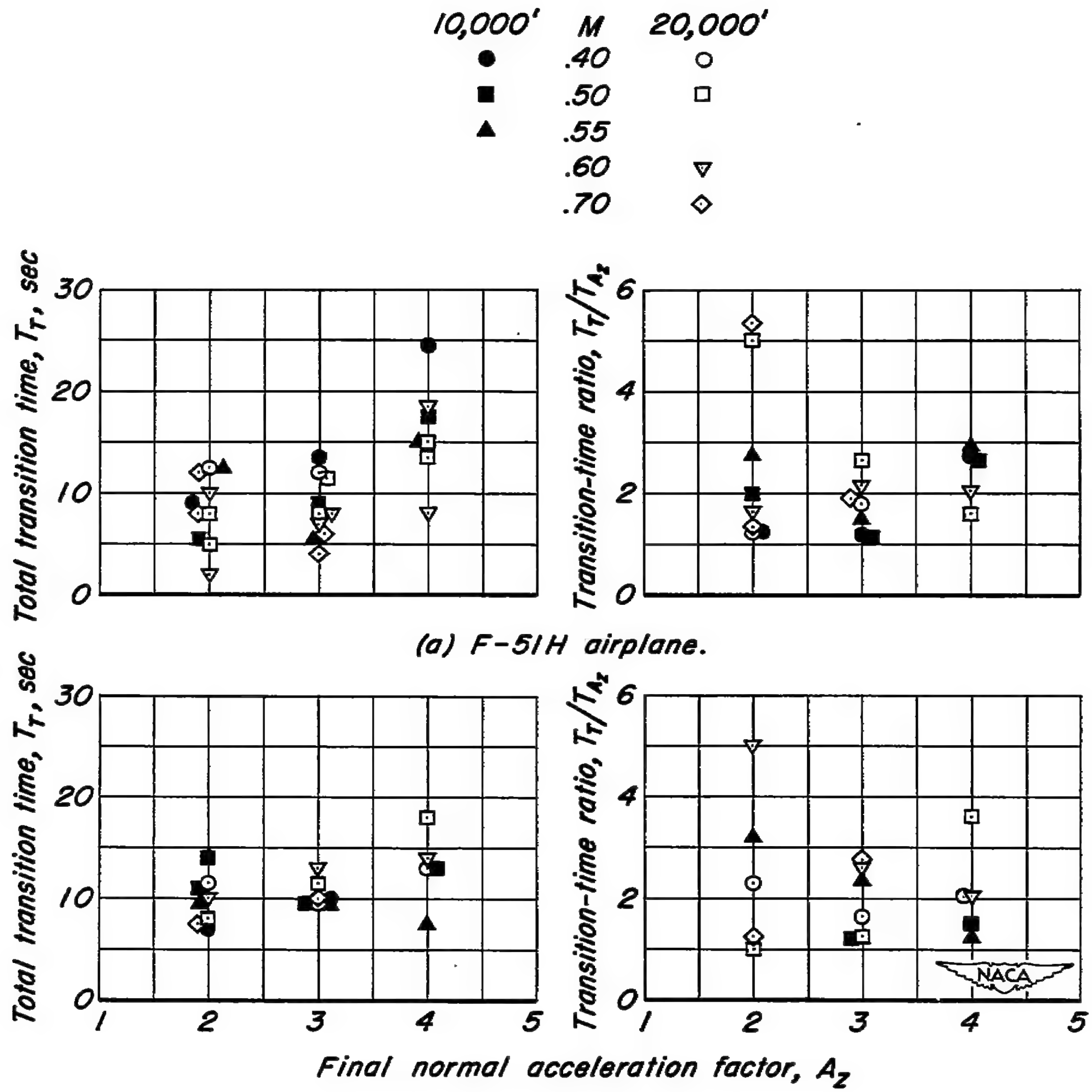
[redacted]



(b) Control-surface motions.

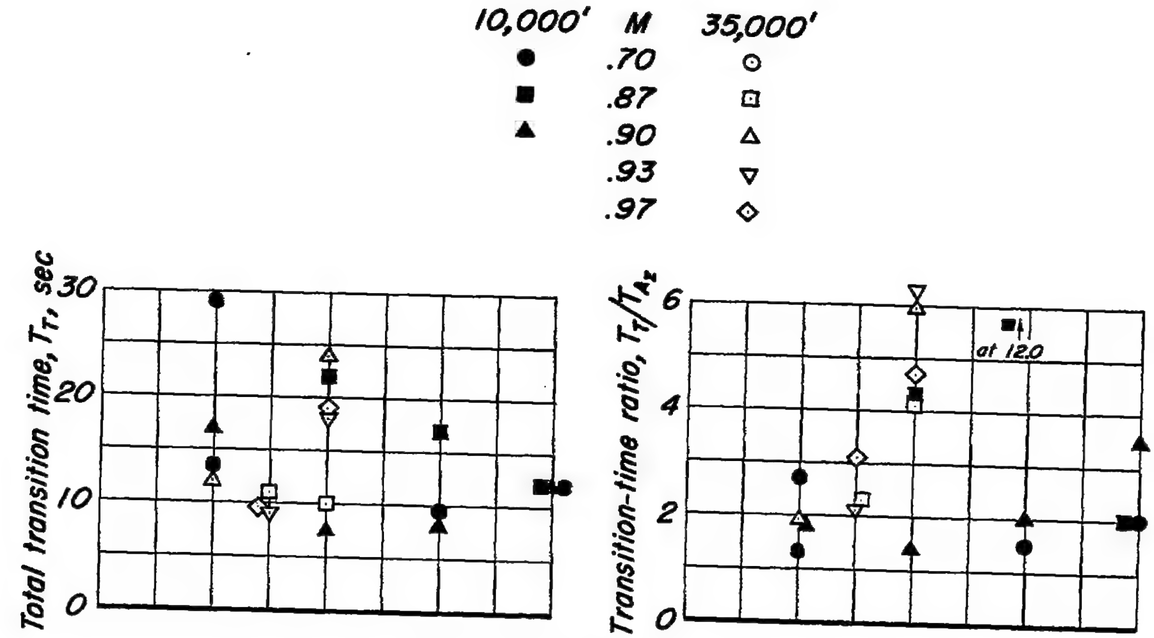
Figure 17.—Concluded.

[redacted]

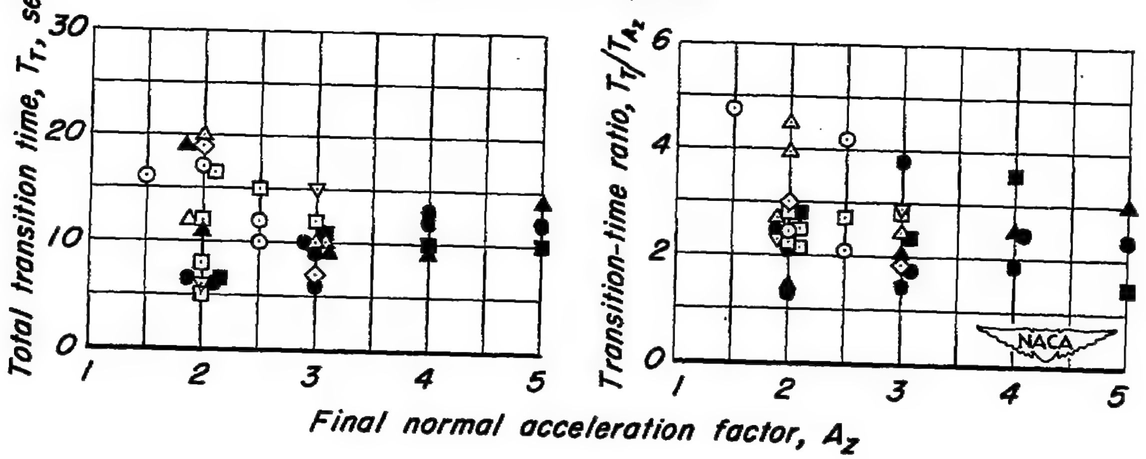


(b) F8F-1 airplane.

Figure 18.— Total transition times and transition-time ratios, pilot A.

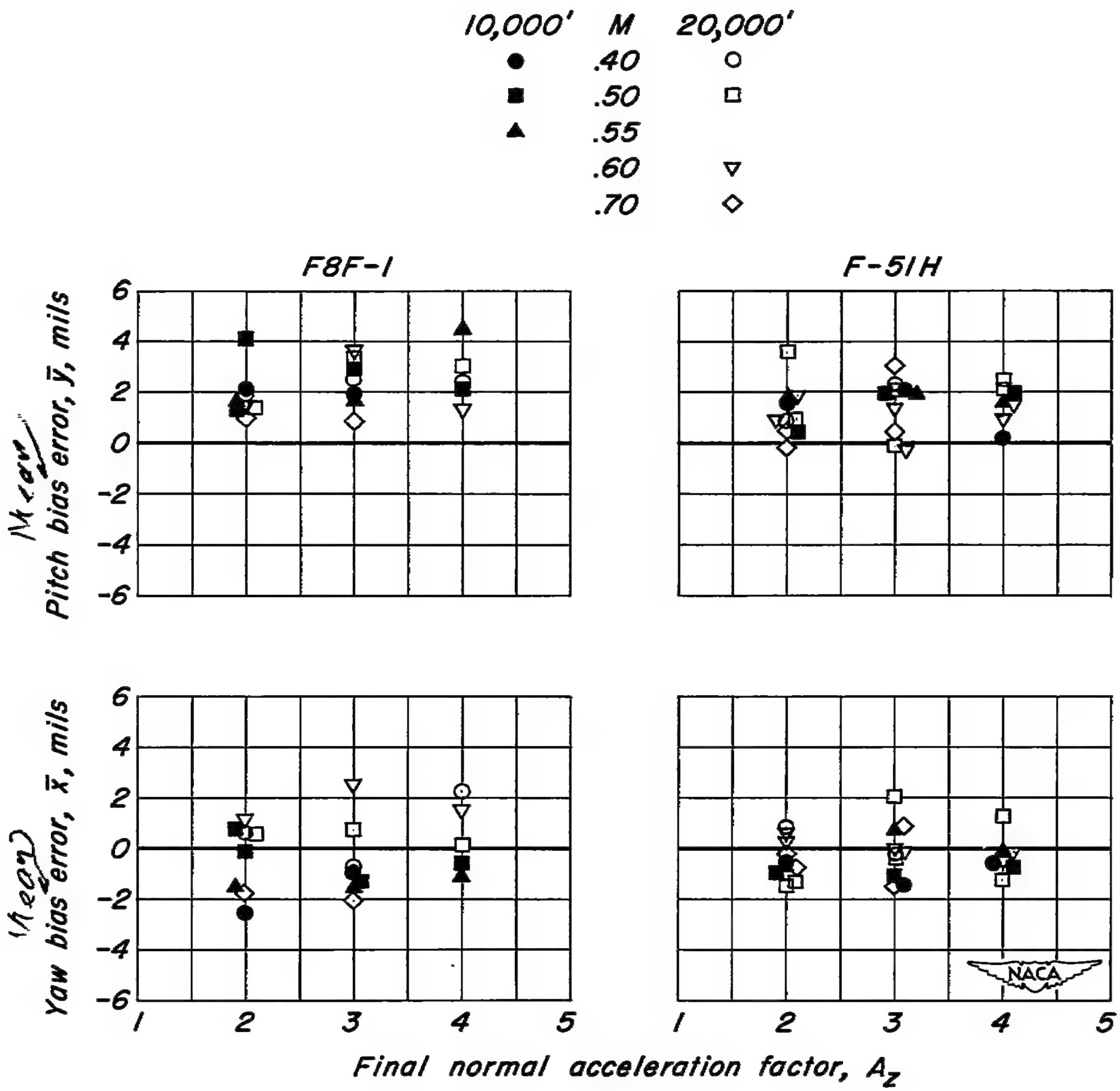


(c) F-86A airplane.



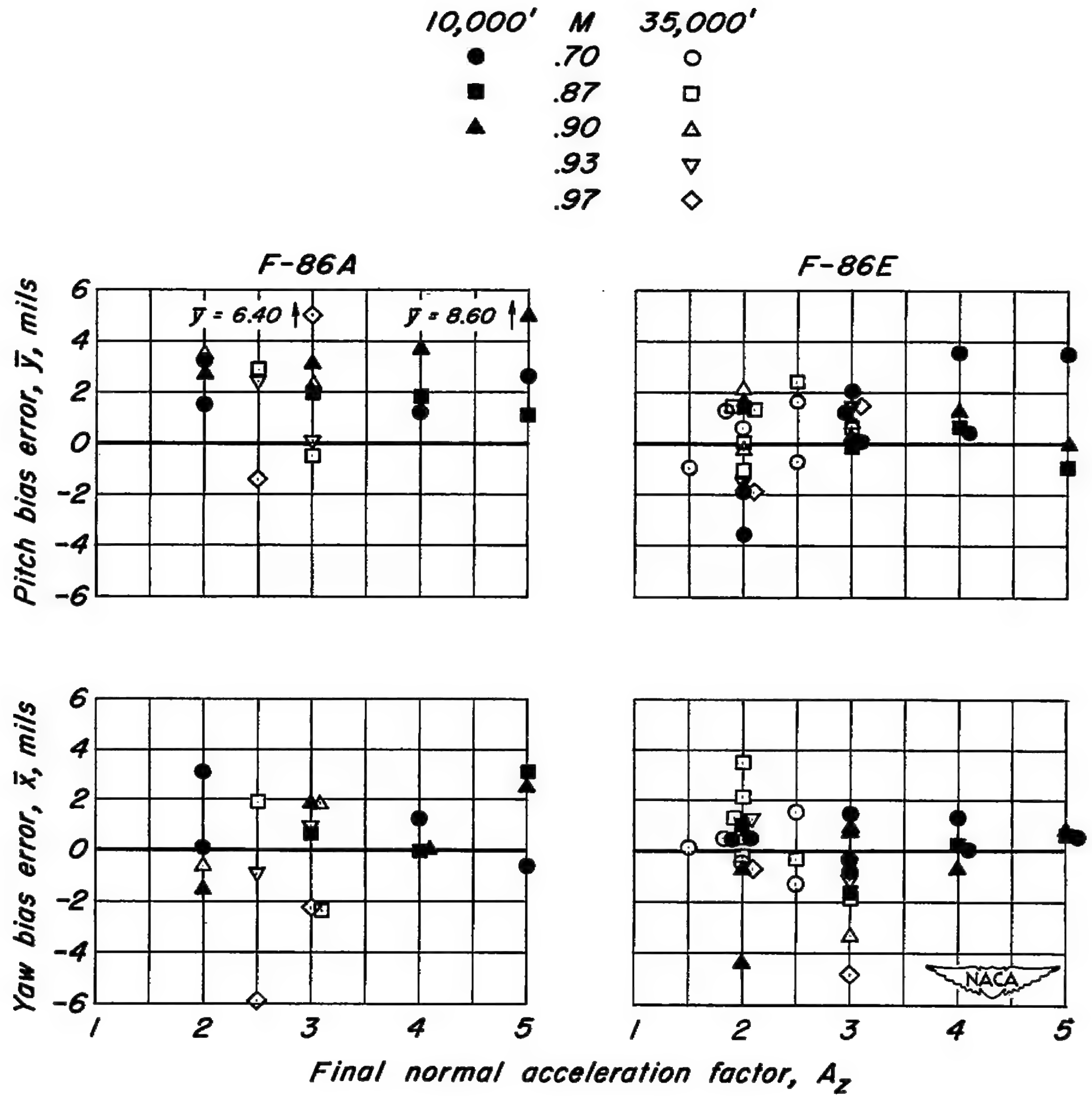
(d) F-86E airplane.

Figure 18.– Concluded.



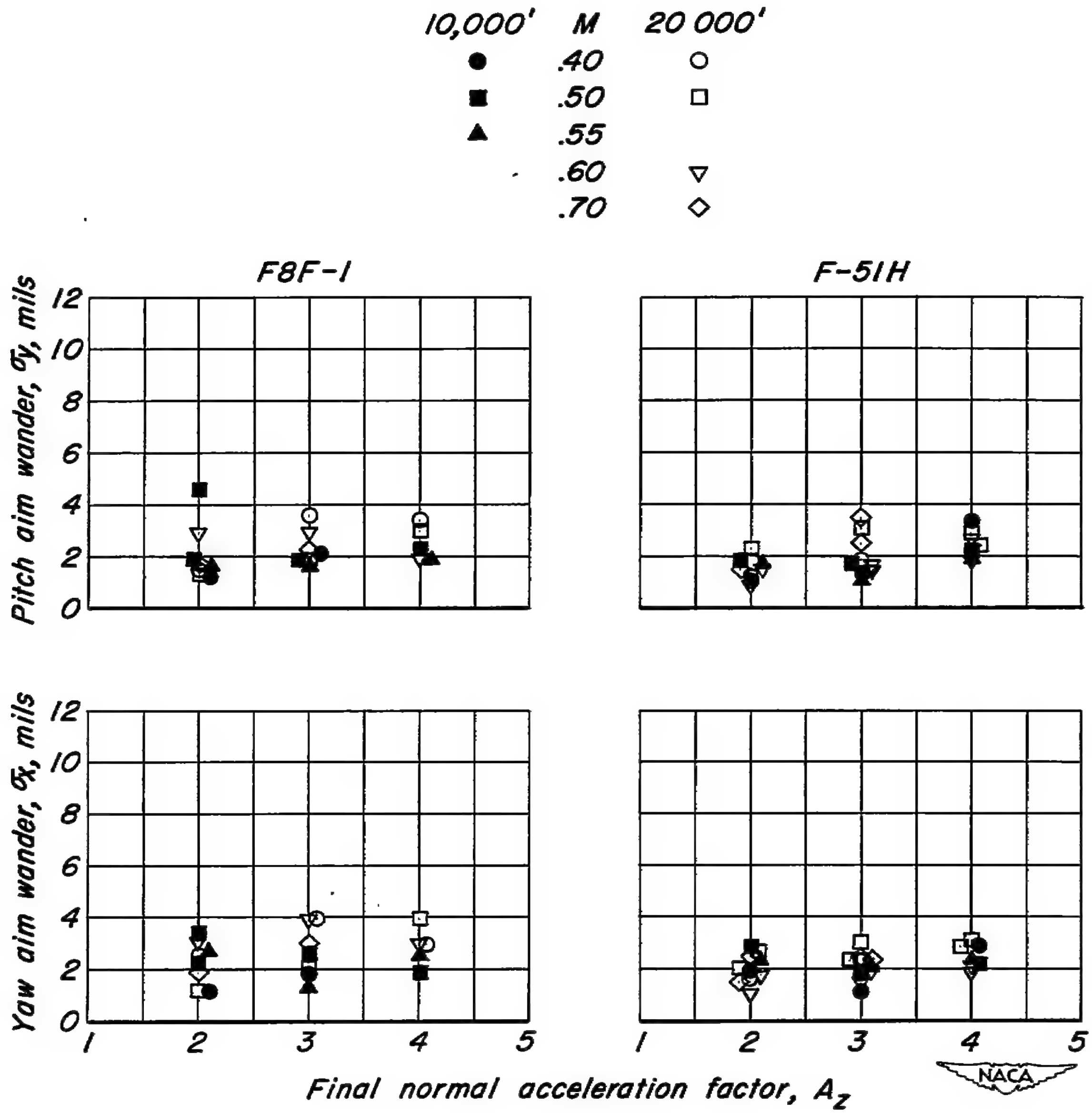
(a) F8F-1 and F-51H airplanes, pilot A.

Figure 19.— Bias errors in the transition region.



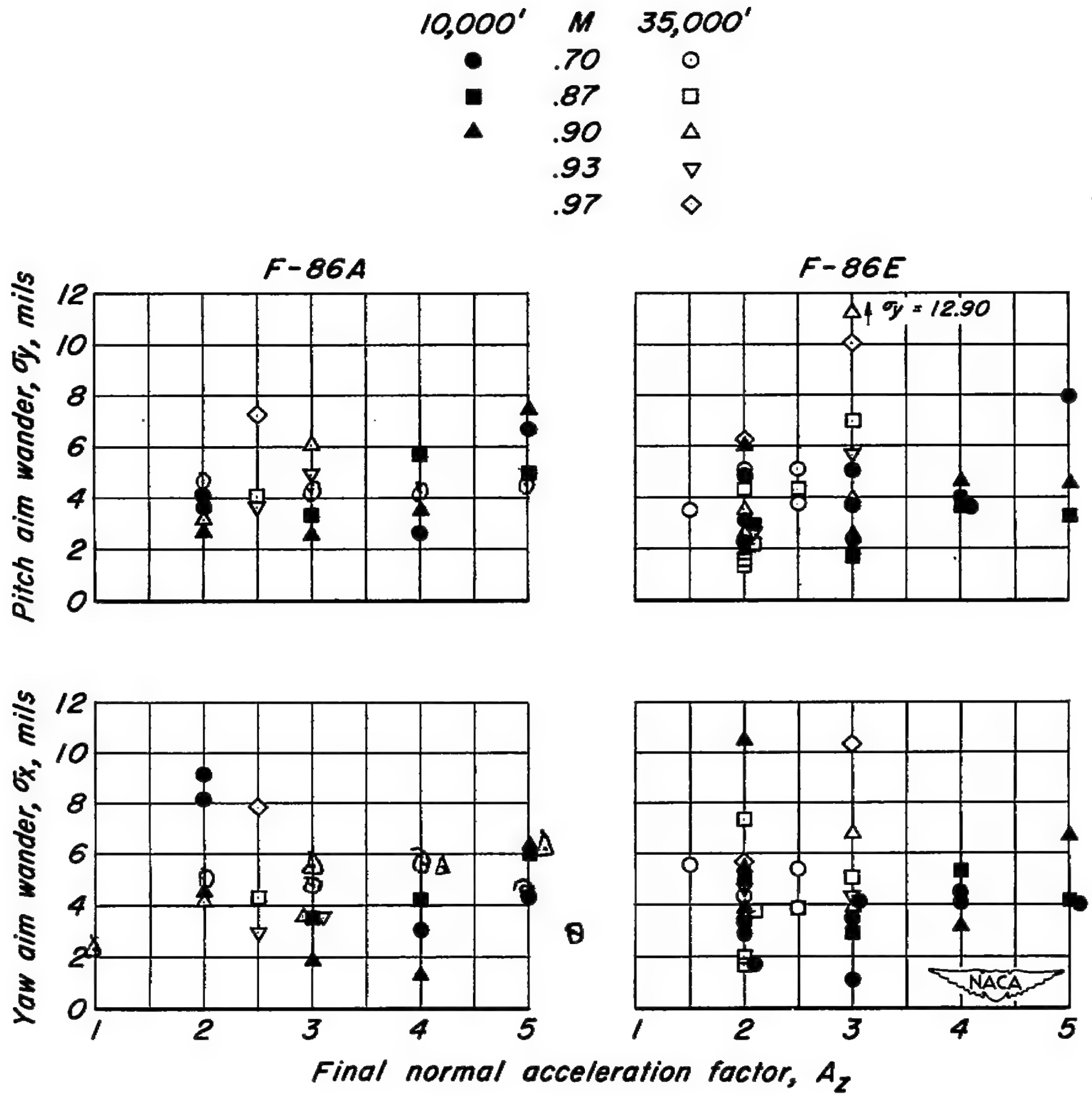
(b) F-86A and F-86E airplanes, pilot A.

Figure 19.— Concluded.



(a) F8F-1 and F-51H airplanes, pilot A.

Figure 20.— Aim wander in the transition region.

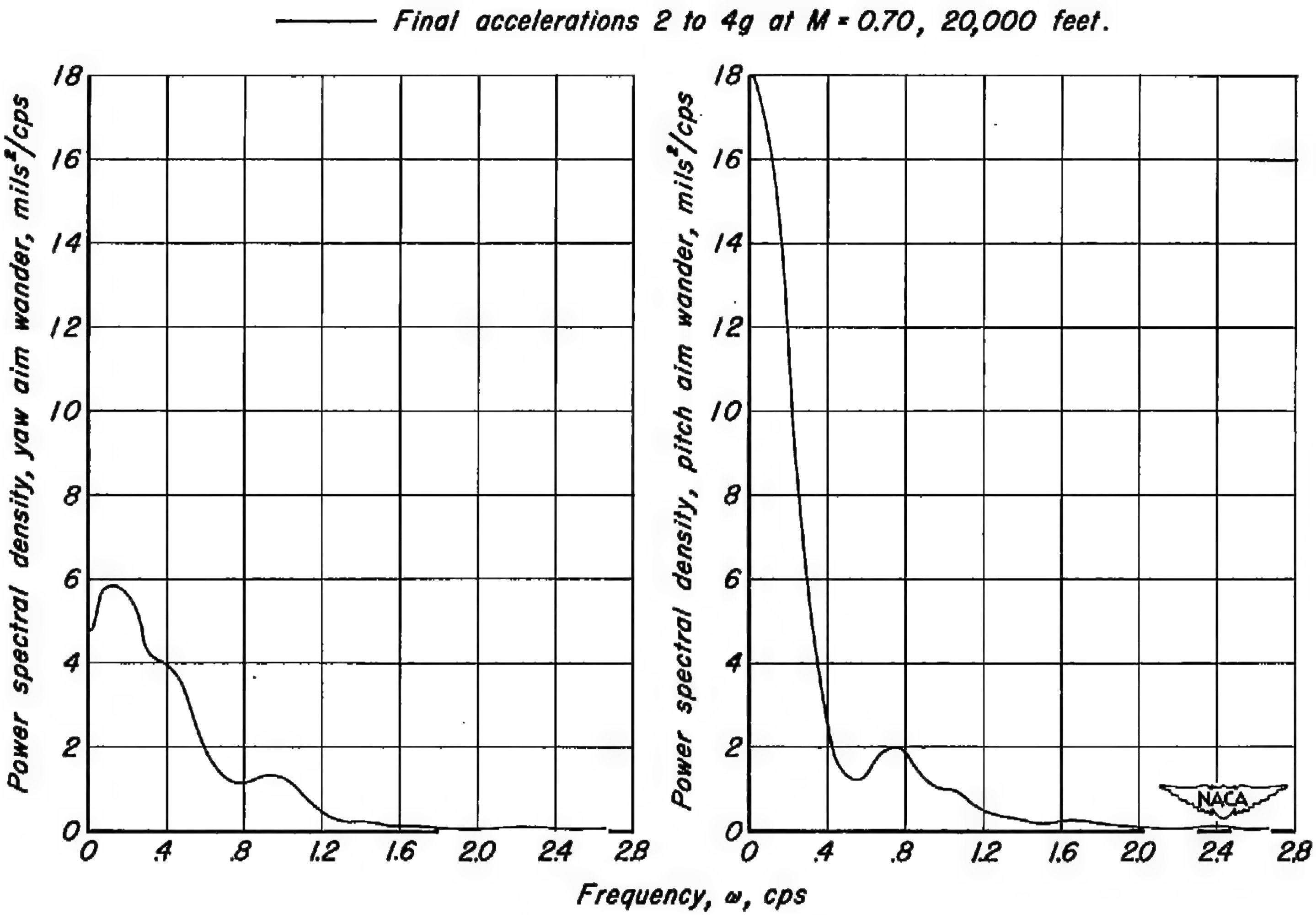


(b) F-86A and F-86E airplanes, pilot A.

Figure 20.– Concluded.

[redacted]

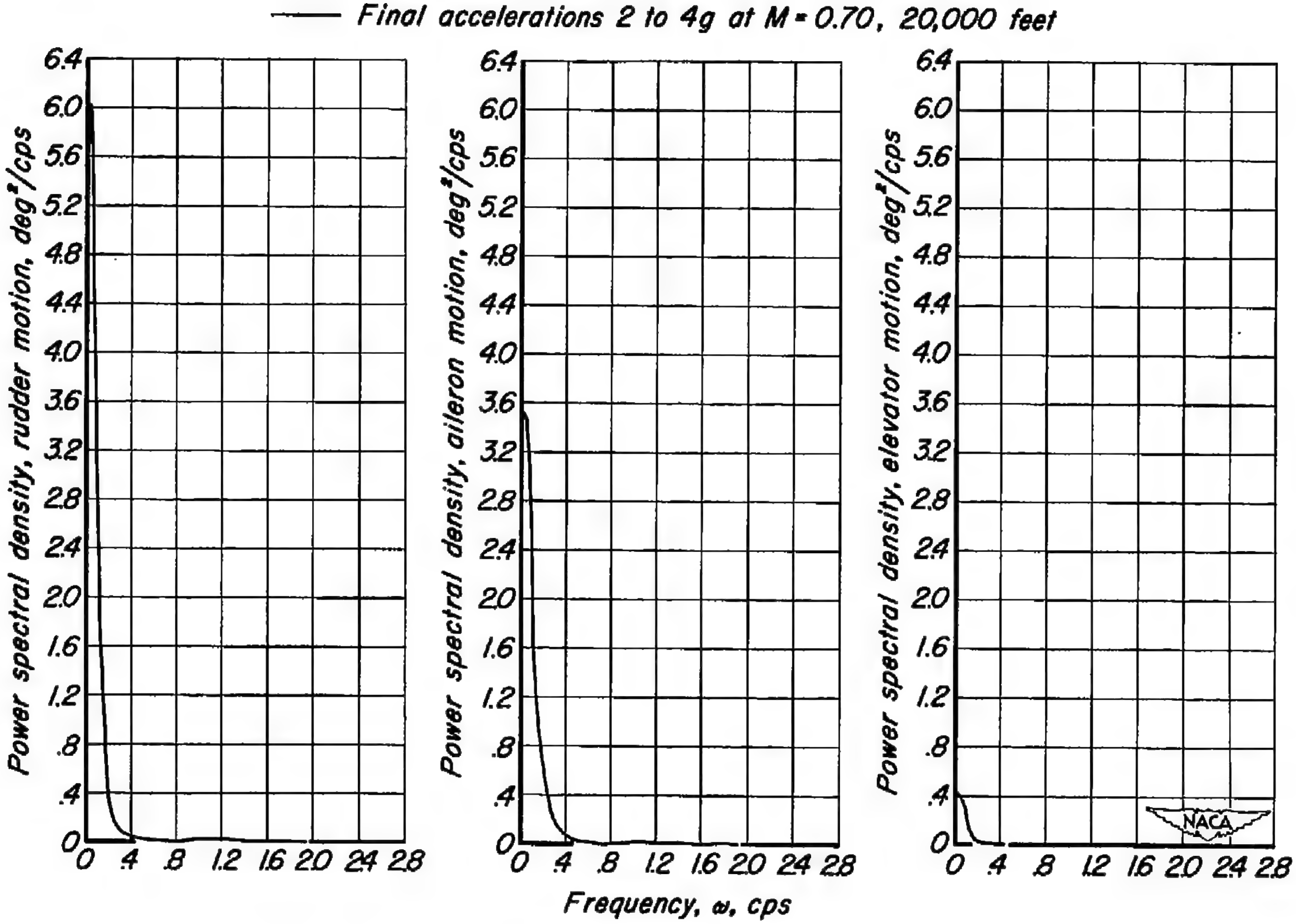
[redacted]



(a) Aim wander.

Figure 21.— Typical power spectral densities of aim wander and control-surface motions for the F-51H airplane under transition conditions.

[redacted]

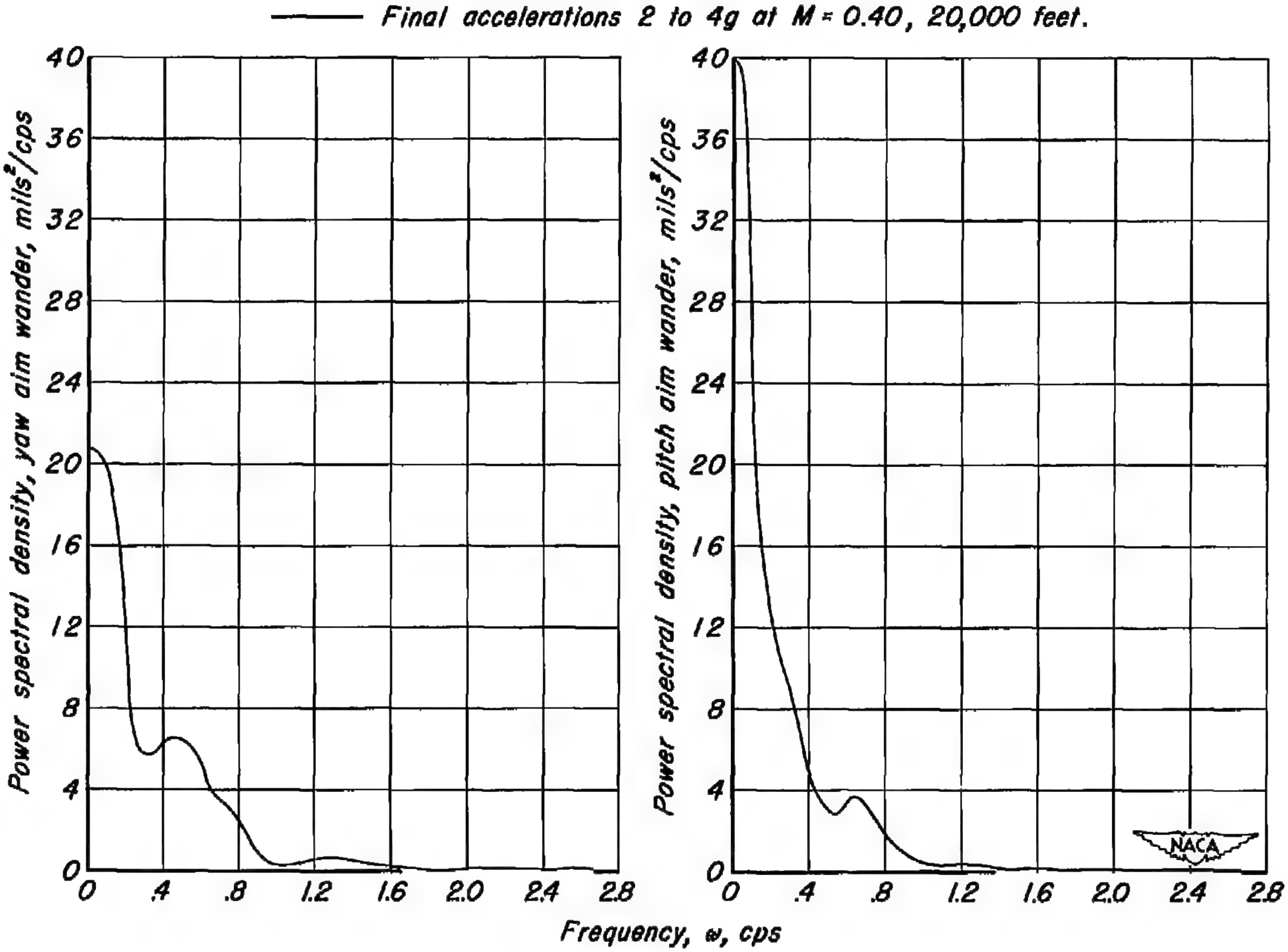


(b) Control-surface motions.

Figure 21.— Concluded.

[redacted]

[redacted]

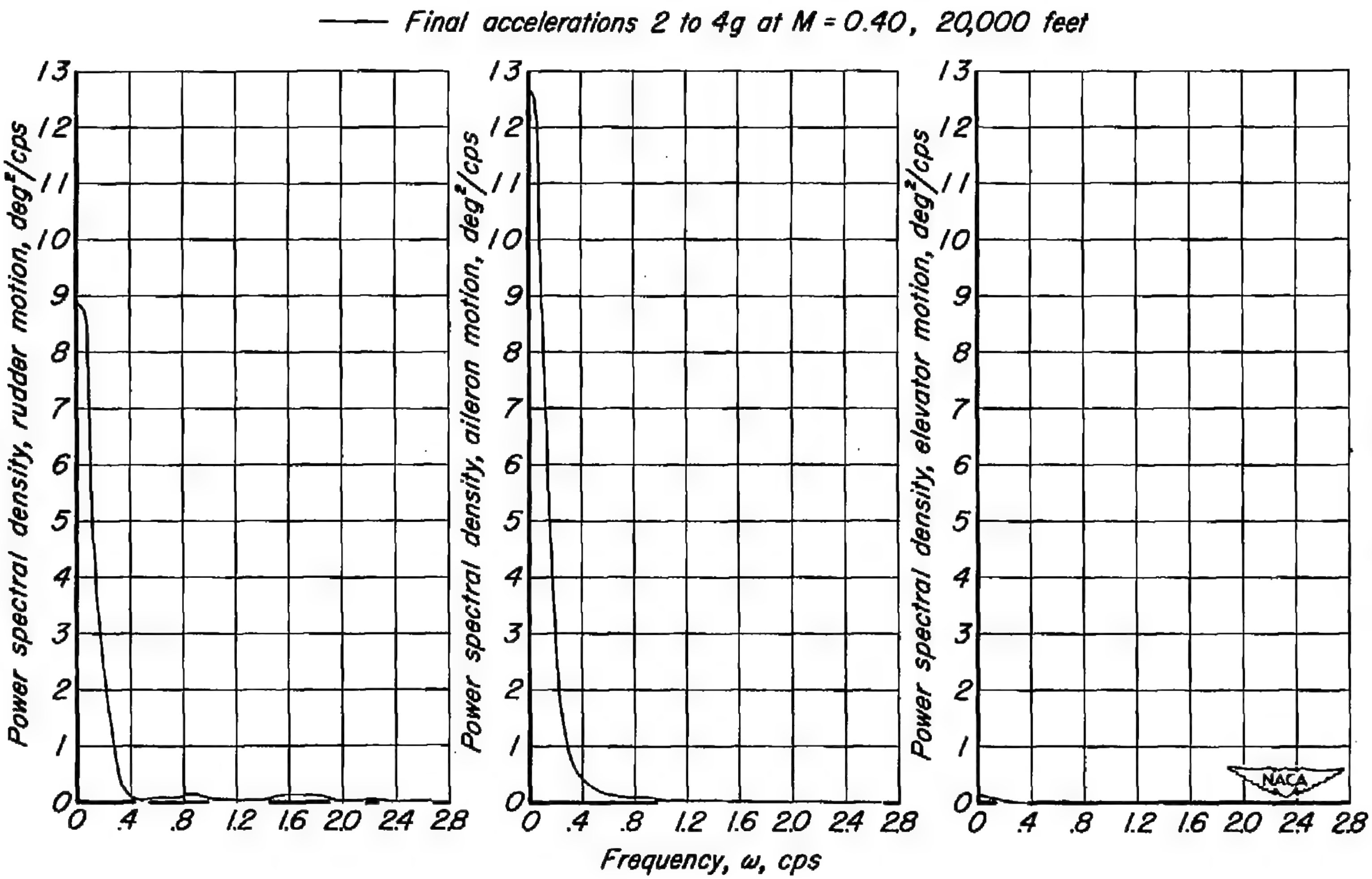


(a) Aim wander.

Figure 22.—Typical power spectral densities of aim wander and control-surface motions for the F8F-1 airplane under transition conditions.

[redacted]

[redacted]

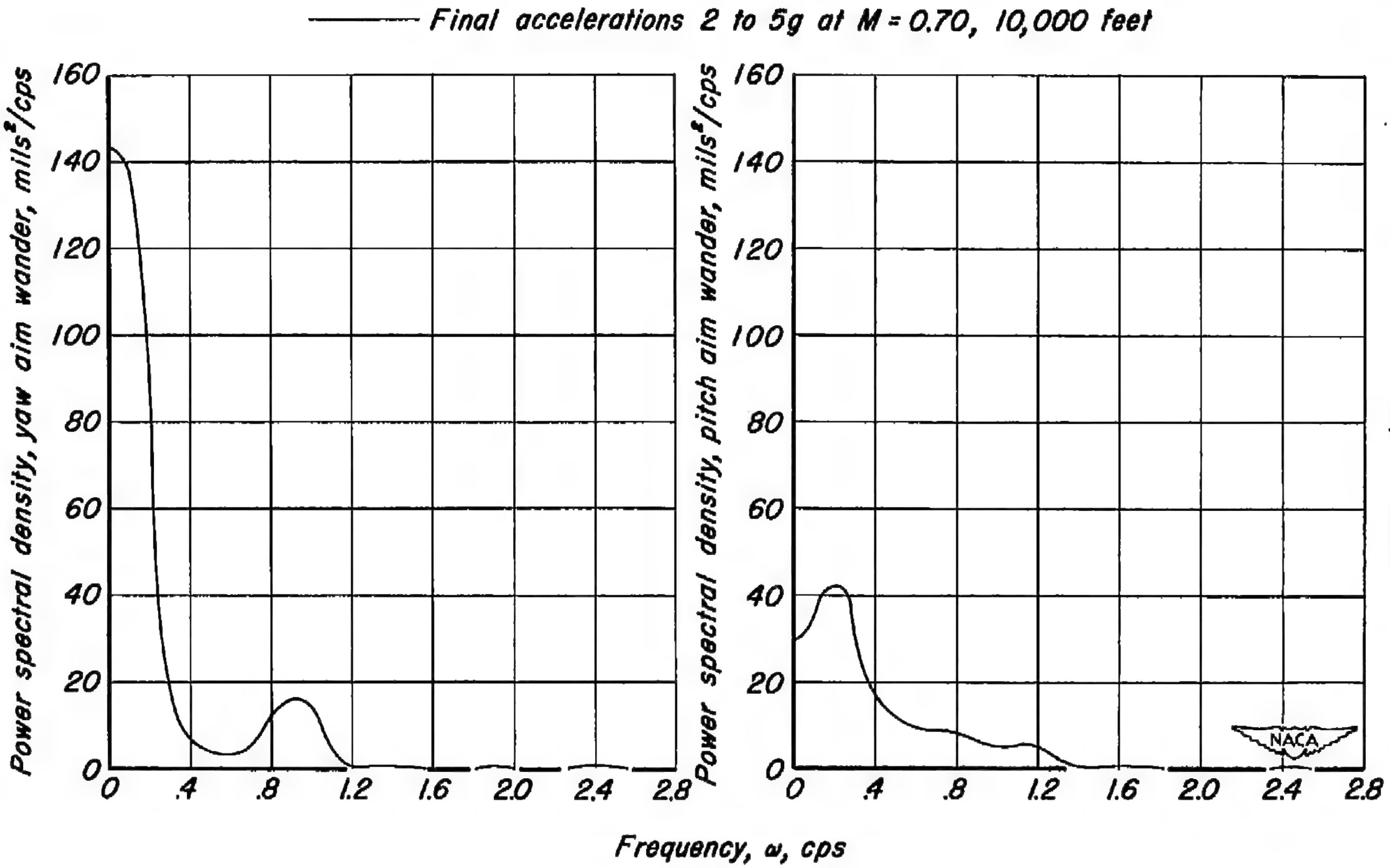


(b) Control-surface motion.

Figure 22.—Concluded.

[redacted]

[redacted]

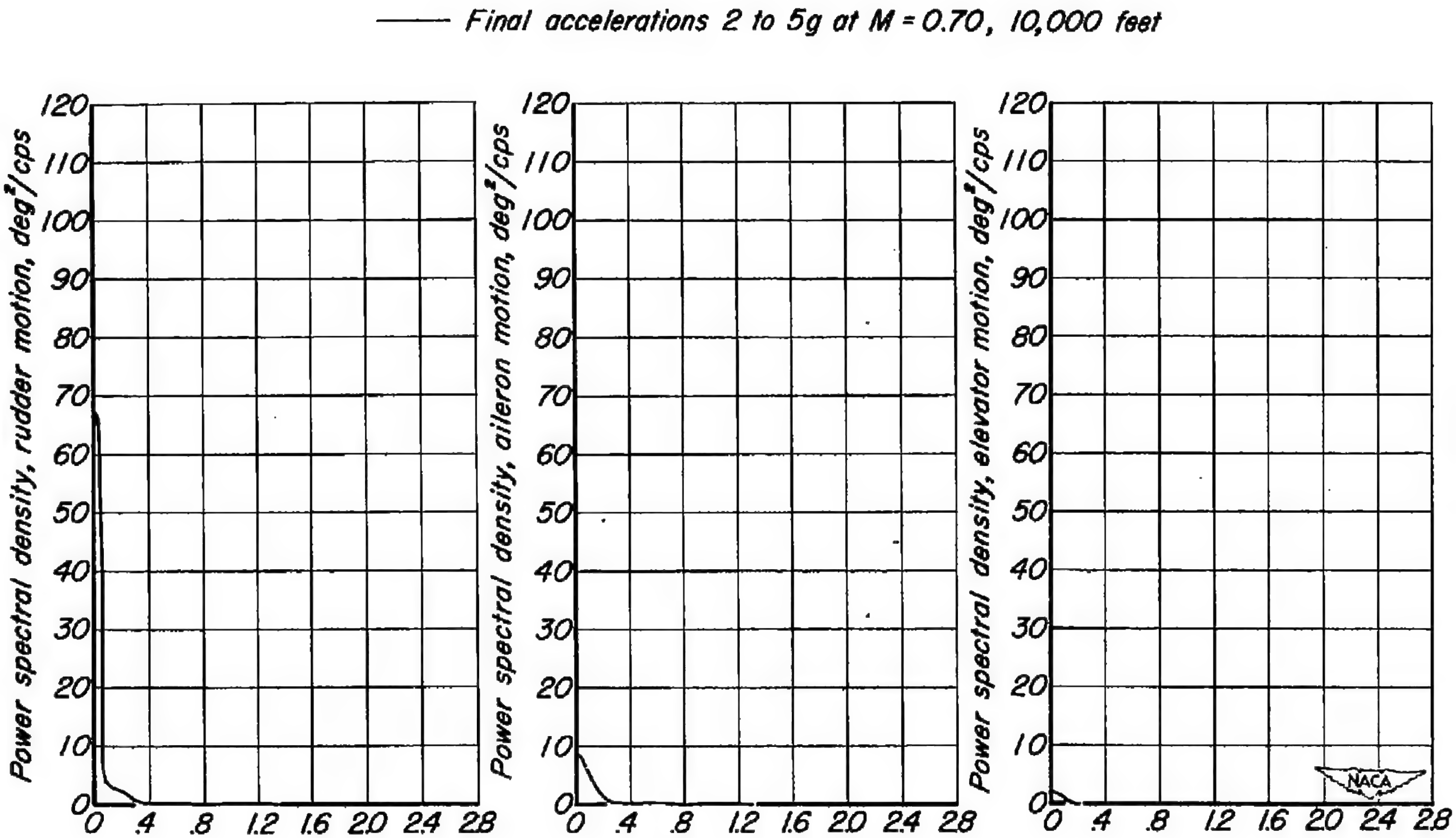


(a) Aim wander.

Figure 23.— Typical power spectral densities of aim wander and control-surface motions for the F-86A airplane under transition conditions.

[redacted]

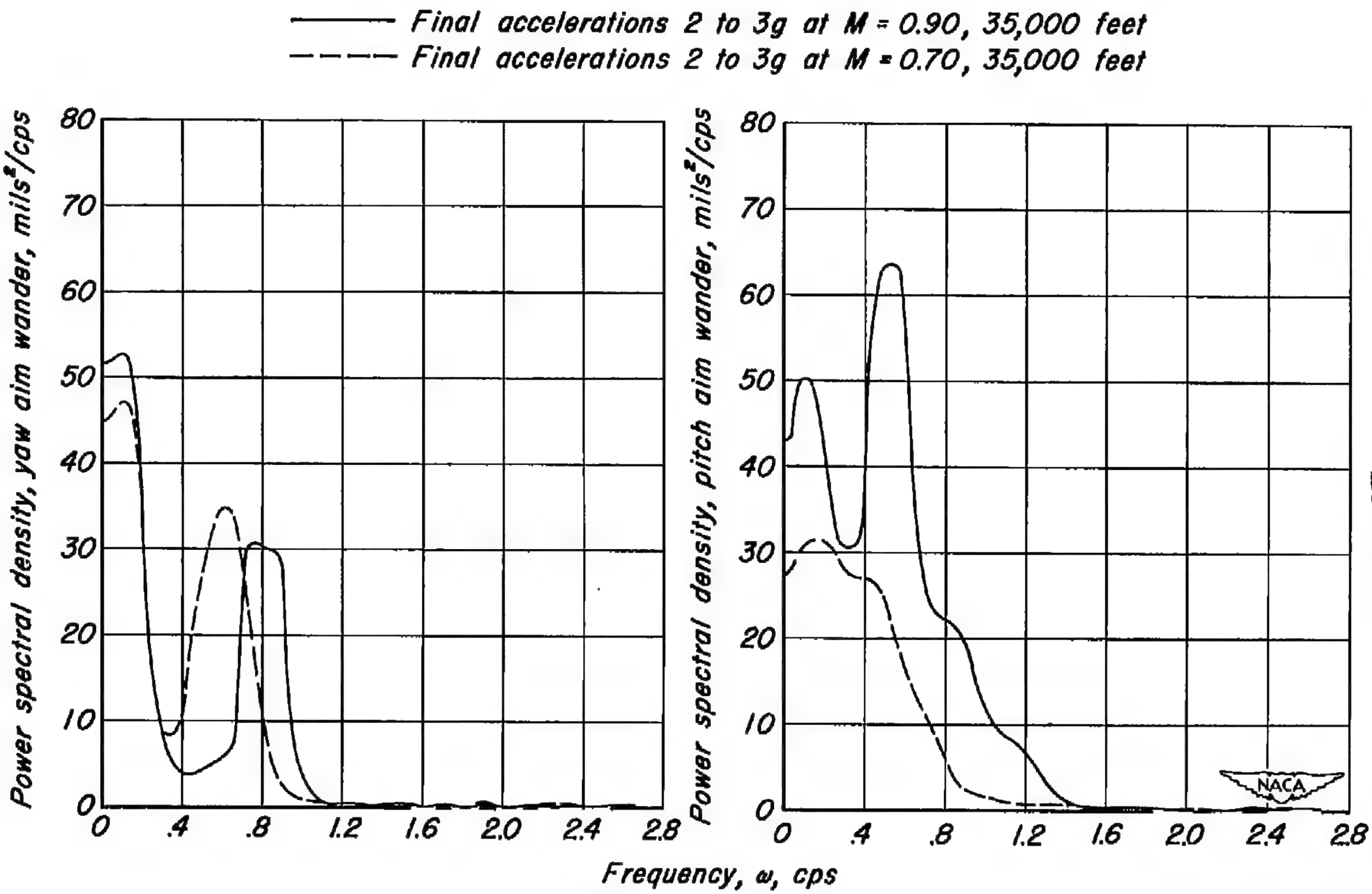
[redacted]



(b) Control-surface motions.

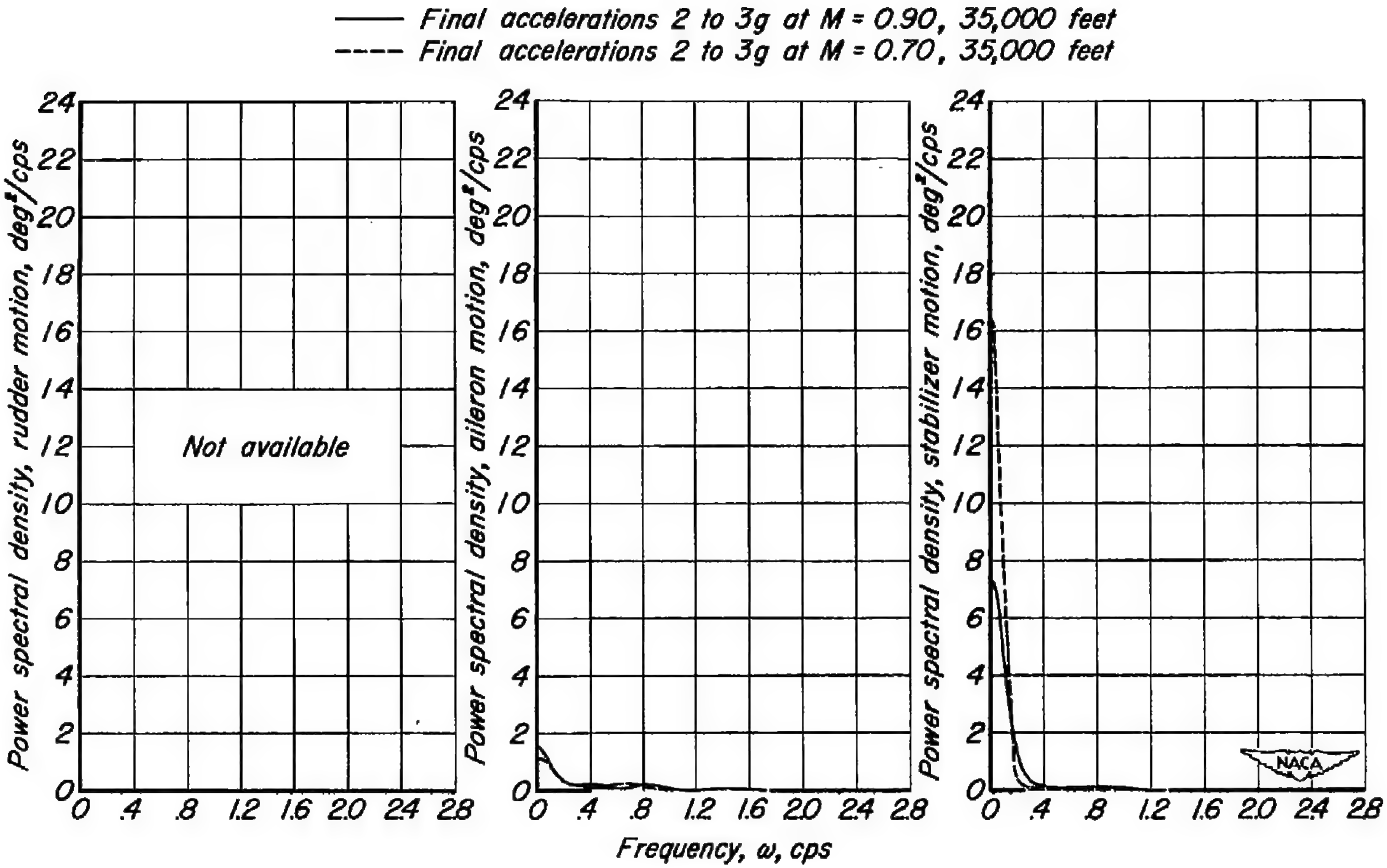
Figure 23.— Concluded.

[redacted]



(a) Aim wander.

Figure 24.– Typical power spectral densities of aim wander and control-surface motions for the F-86E airplane under transition conditions.



(b) Control-surface motions.

Figure 24.—Concluded.

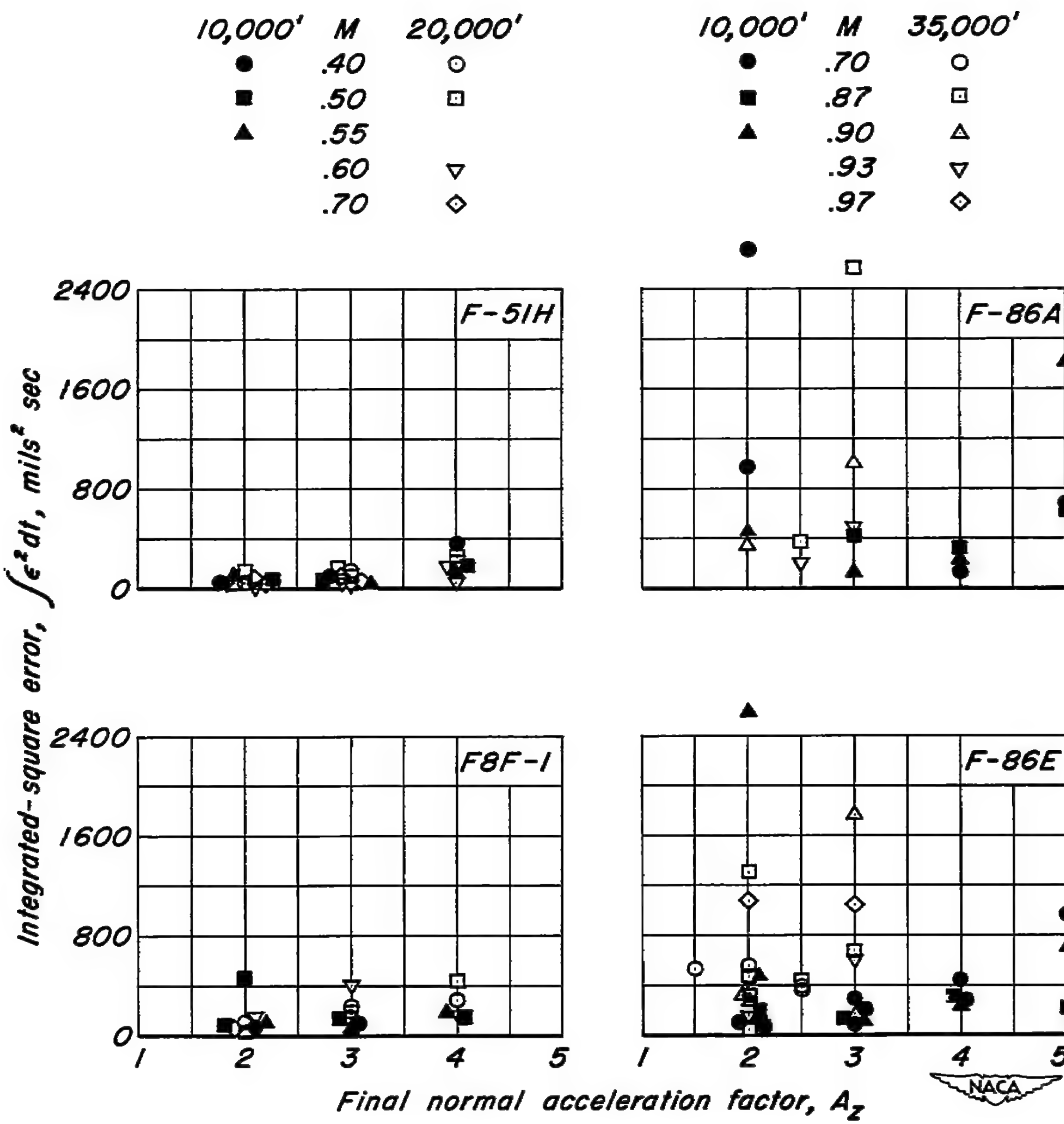


Figure 25.—The variation of integrated-square error with final normal acceleration, in the transition region, pilot A.

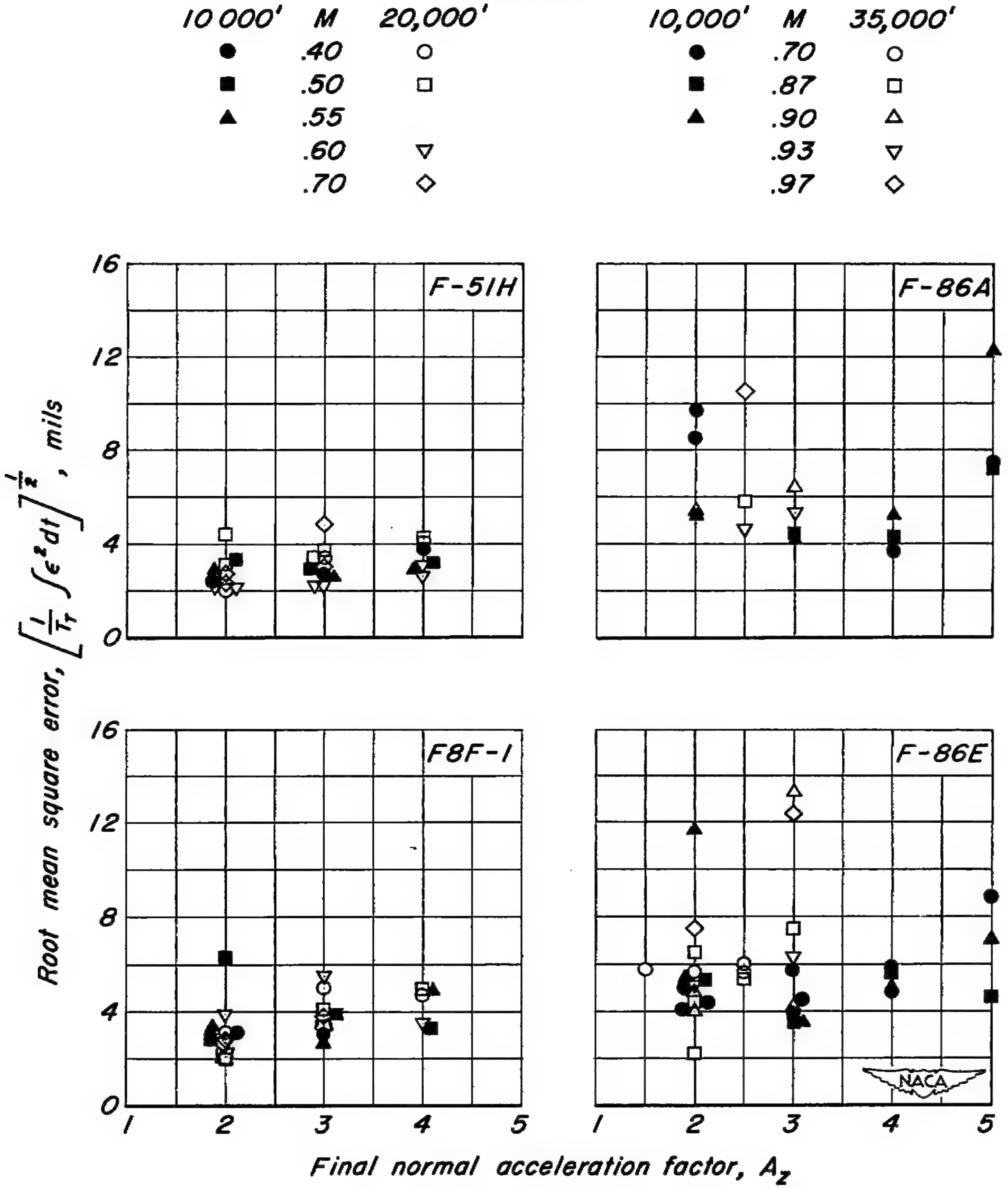


Figure 26.—The variation of root mean square error with final normal acceleration, in the transition region, pilot A.

[redacted]

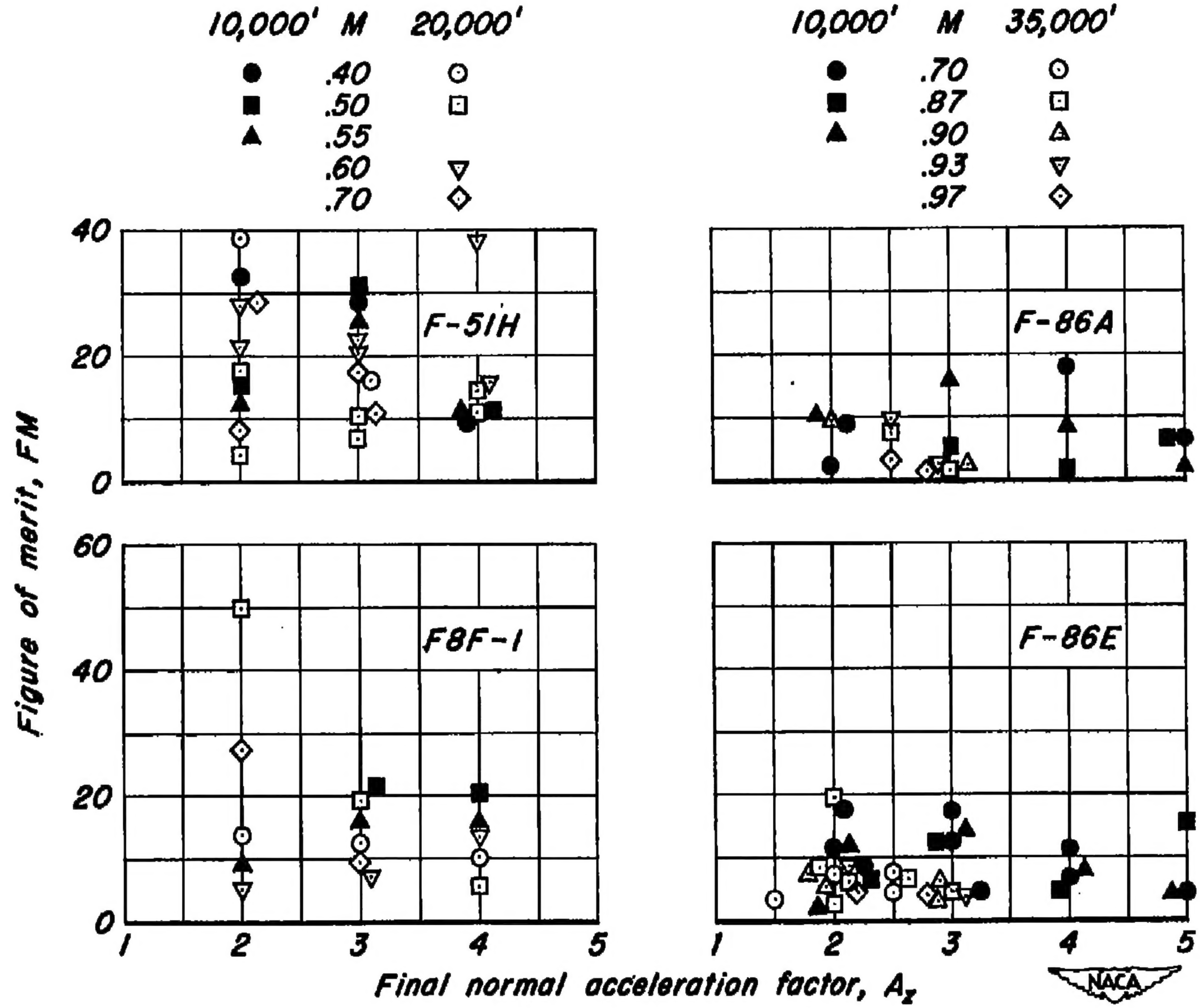


Figure 27.— The "figure of merit" for the transition region for all four airplanes.

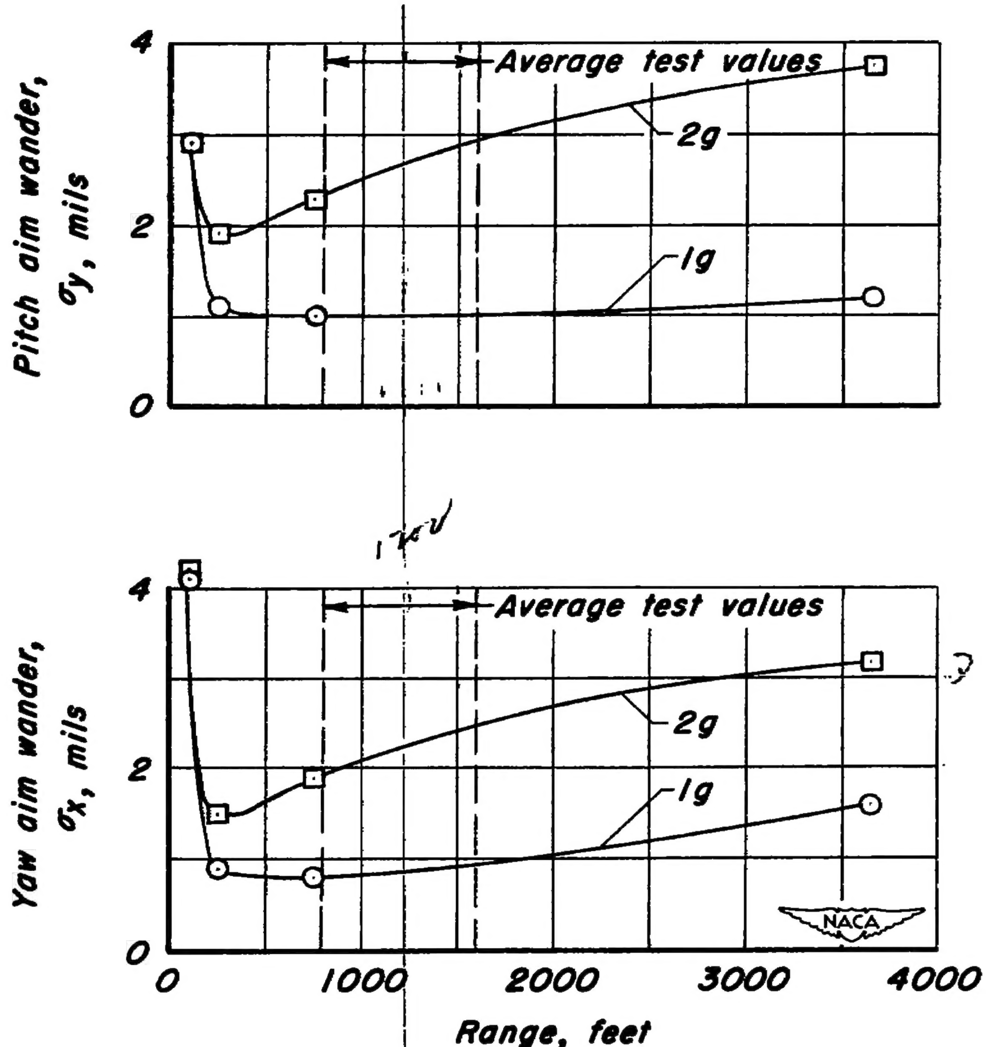
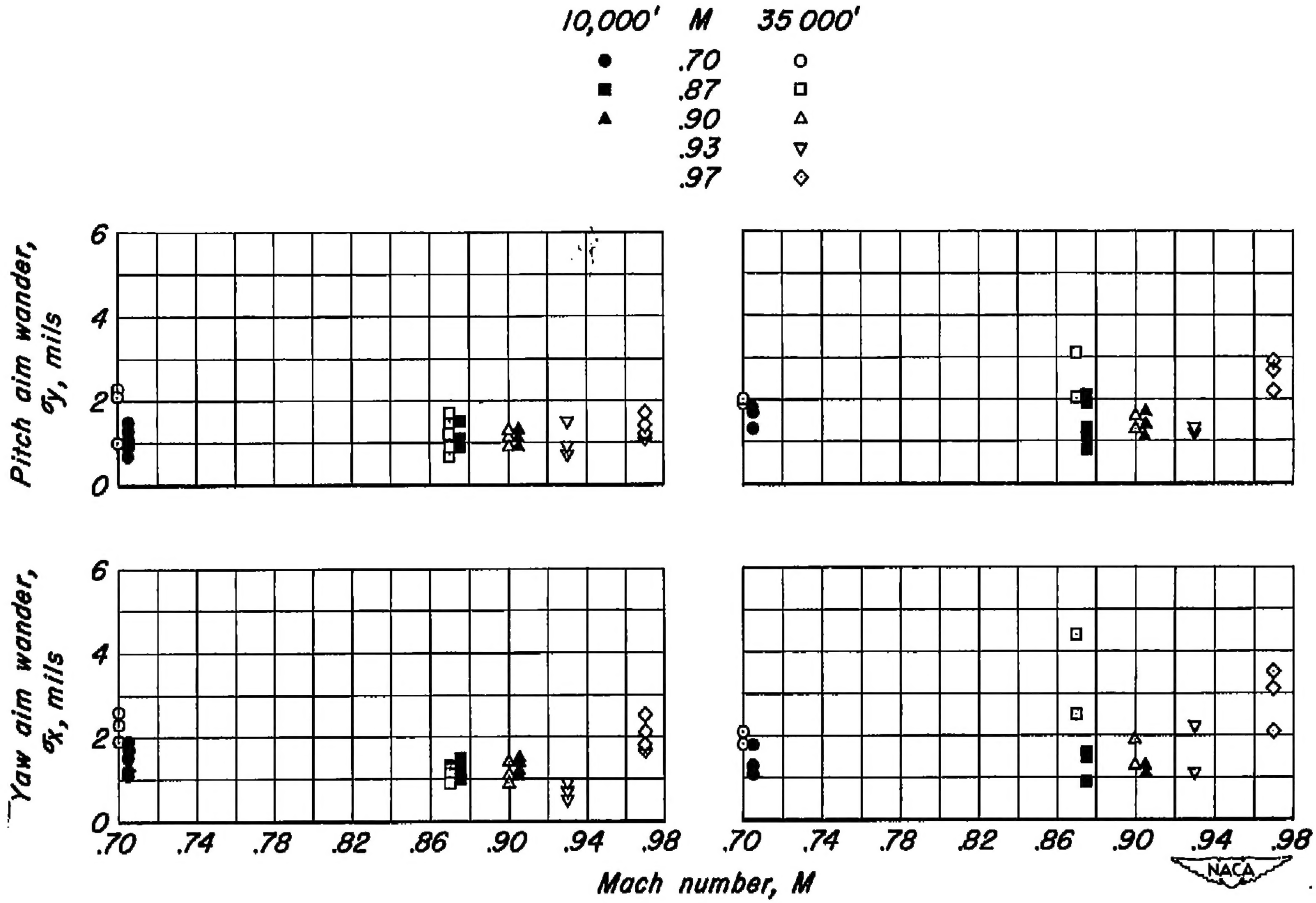


Figure 28.— The effect of range on aim wander during steady conditions, F-86E airplane, 0.87 Mach number, 35,000 feet altitude, pilot A.

[redacted]



(a) Pilot A.

(b) Pilot B.

Figure 29.— Repeatability of data for steady-state 1g flight. F-86E airplane.